Renewable and Sustainable Energy Reviews 23 (2013) 12–39

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of studies on central receiver solar thermal power plants

Omar Behar [a,*], Abdallah Khellaf [b], Kamal Mohammedi [a]

[a] L.E.M.I Laboratory, University of M'hamed Bougara, UMBB, Boumerdes, Algeria
[b] Centre de Développement des Energies Renouvelables, CDER, Bouzareah, Algeria

ARTICLE INFO

Article history:
Received 16 September 2012
Received in revised form
31 January 2013
Accepted 3 February 2013
Available online 19 March 2013

Keywords:
Central receiver system
Heliostat field
Solar receivers
Power conversion system
Concentrating solar power

ABSTRACT

The use of central receiver system (CRS) for electricity production promises to be one of the most viable options to replace fossil fuel power plants. Indeed, research and development activities on its basic subsystems have been booming rapidly since 1980s. This paper reviews the most important studies on the major components of central receiver solar thermal power plants including the heliostat field, the solar receiver and the power conversion system. After an overview of Concentrating Solar Power (CSP) technology, current status and applications of the CRSs are highlighted. Next, a detailed literature survey of existing design comprising optical, thermal and thermodynamic analysis, and techniques used to assess components have been arranged. This is followed by experimental investigations in which design concepts are established. The last section contains recent subsequent improvement of such key components as heliostat, receiver and hybrid solar gas turbine that are boosting in many R&D activities merging international collaboration during the past 30 years.

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* Corresponding author. Tel.: +213 555 82 71 29.
E-mail addresses: beharomar@yahoo.fr, beharomar@gmail.com (O. Behar).

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http://dx.doi.org/10.1016/j.rser.2013.02.017

1. Inroduction: Why concentrating solar power (CSP)?

It is obvious that the origin of climatic change is CO_2, and at least 90% of its emission amount results from fossil fuels burning for power generation and transport sector [1–4]. Recent studies and technology roadmaps published by the International Energy Agency (IEA), the German Aerospace Center (DLR) and the European Union (EU) have projected that 80% of the CO_2 emissions, by 2035, will be from current industry-based economy; so that changes in the climate will intensify if no decisive actions are undertaken [1,4–6]. The progressive build up of CO_2 in the atmosphere is the undisputed cause for temperature rise accentuation, the melting of the polar ice caps and the increase in extreme weather events worldwide [1,4–6]. As a result, many people around the World, mainly in Africa, face an increasing risk of hunger, water shortages, flooding, desertification, and severe environmental pollutions that are expected to cause about 150,000 additional deaths every year [3]. It has to be though stated that the fossil fuel era have resulted in an unparalleled standard of living and an increased life expectancy for part of the world's population [1,5,7].

Meanwhile, petroleum and natural gas prices are projected to move forward in the next 20 years (from \$125/barrel in 2011 to over \$215/barrel in 2035 [1]). This is due to increased demand which set to grow by over 50%; from 87.4 mb/d in 2011 to 99.7 mb/d in 2035 [1]. Cconsequently, energy-related CO_2 emissions will then more than double by the year 2050 and concerns over supply security will surely heighten [1,6,8]. More than 7 billion people consume far more fossil resources and produce far more pollution than the Earth can accommodate [4,5]. For instance, in the Mediterranean region energy consumption is raised by a factor of three between 1980 and 2005, and a further doubling is intended by 2020 [9].

Furthermore, catastrophic events such as those at the Fukushima Daiichi nuclear power plant, in March 2011, and the turmoil in parts of the Middle East and North Africa (MENA) have forced many countries around the world to review their policies and retreat from nuclear power. This is particularly true for Germany. As a consequence, the nuclear energy share in the global electricity mix is dropping down and the global energy map changing [1,2].

For these reasons, more and more countries are mandating that a part of the electric power be from renewable origin, in particular solar energy. [10–28]. According to IEA, 50% of the new power infrastructures will base on clean-sustainable energies. As a result, renewable energy will become the world's second-largest source of power generation by 2015; delivering about 30% of the electricity needs by the year 2035 [1].

Nowadays, concentrating solar power (CSP) technology implantation is growing faster than any other renewable technology. This is because, as shown in Figs. 1–3, it offers an integrated solution to the coming decade's global problems, i.e., climate change and associated shortage of energy, water and food [1,5,12,27–32]. For instance, a one megawatt of installed CSP avoids the emission of 688 t of CO_2 compared to a combined cycle system and 1360 t of CO_2 compared to a coal/steam cycle power plant. A one square mirror in the solar field produces 400 kW h of electricity per year, avoids 12 t of CO_2 emission and contributes to a 2.5 t savings of fossil fuels during its 25-year operation lifetime. [33,34]

2. Background

2.1. Concentrating solar power (CSP): Historic and current status

2.1.1. Historic

Concentrating solar power (CSP) is not an innovation of the last few years. Records of its use date as far back as 212 BC when Archimedes used mirrors for the first time to concentrate the Sun's rays [35]. In the early seventeenth century, Salomon De Caux developed in 1615 a small solar powered motor consisting of glass lenses and an airtight metal vessel containing water and air [35]. More than a century later, in 1774, Lavoisier and Joseph Priestley developed the theory of combustion by concentrating solar radiation on a test tube for gas collection [36]. Next, Augustin Mouchot has devised a solar steam machine to run a printing press [37]. After that, in 1878, a small solar power plant made up of a parabolic dish concentrator connected to an engine was exhibited at the World's Fair in Paris [38]. In the early 1900s, although interest in solar power was then lost due to advances in internal combustion engines and increasing availability of low cost fossil fuel, the first CSP-plant, powered by a parabolic trough solar field, was installed at Al Meadi (Egypt)[39,40]. This first CSP-plant, installed in 1913, was used for pumping water for irrigation [39,40]. In the 1960s, with the focus on photovoltaic for the space program, interest in solar energy began to arise again. During 1970s the oil crisis boosted R&D activities on CSP and numerous pilot plants were built, tested and bringing CSP technology to the industrial and commercial level [41]. As a result, the first commercial plants had operated in California (USA) over the period of 1984–1991, spurred, more particularly, by federal and state tax incentives and mandatory long-term power purchase contracts. A drop in oil and gas prices has though driven many countries to retreat from the policy that had supported the advancement of CSP, and thus, no new plants have been built between 1990 and 2000. It was not until 2006 that interest was once again rekindled for the development of large scale CSP-plants. The market re-emerged more particularly in Spain and the United States, again in response to government measures such as the feed-in tariffs (Spain) and the policies requiring a share of

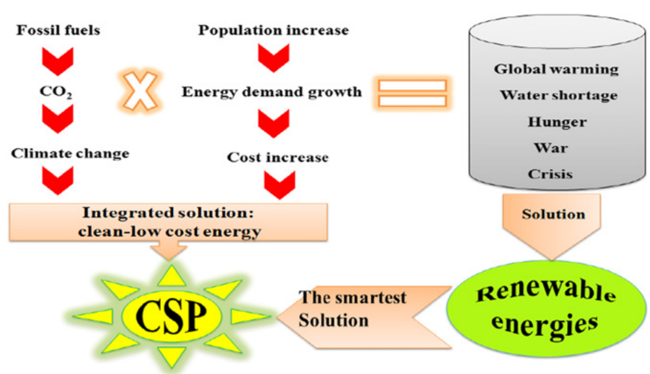

Fig. 1. CSP offers an integrated solution to global problems of the coming decades.

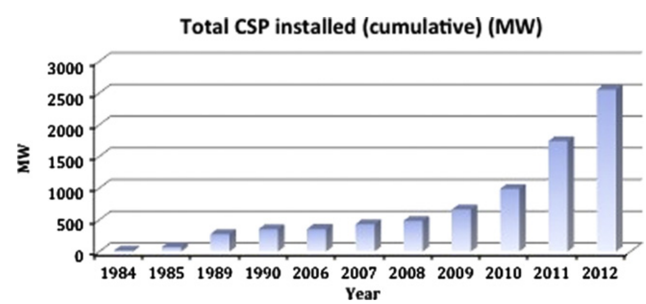

Fig. 3. installed solar thermal power plants since the 1980s [32].

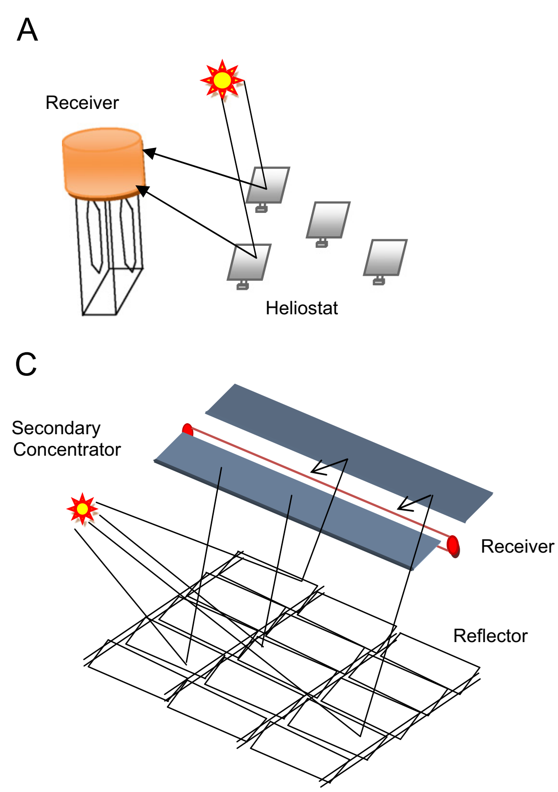

Fig. 2. Basic concept of the four CSP families: (A) central receiver, (B) parabolic trough, (C) linear Fresnel, (D) dish.

solar power in their energy mix. As of 2011, have been worldwide 1.3 GW of CSP plants in operation, 2.3 GW under construction, and 31.7 GW in the planning stage [33].

Nowadays, in 2013, 2.136 GW are operating, 2.477 GW under construction and 10.135 GW are announced mainly in the USA followed by Spain and China [32]. According to reference [34], about 17 GW of CSP projects are under development worldwide, and the United States leads with about 8 GW. Spain ranks second with 4.46 GW in development, followed by China with 2.5 GW.

2.1.2. Basic concept and current status

As shown is Fig. 4, a typical CSP-plant consists of three main subsystems: solar collector field, solar receiver and a power conversion system. In a hybrid plant, back-up and/or storage systems are added to enhance performance and increase capacity factor [13,39,42]. The solar receiver absorbs the concentrated solar radiation by collectors and transfers it to the heat transfer fluid (HTF) which is used to feed high-temperature heat to a power conversion system. The subsystems are linked together by radiation transfer or fluid transport. There are four CSP families depending on the two major solar subsystems, i.e., the collector and the receiver: parabolic trough, solar tower also known as central receiver, linear Fresnel and dish Stirling [6]. They are classified according to the manner they focus the sun's rays and the receiver technology [17,28,33]. A brief comparison between these families is illustrated in Table 1. For each technology the overall efficiency of the whole system varies with the location, the time of day and the day of the year [43–45].

In each CSP family, a variety of options is possible for solar field layout, tracking system, receiver type, heat transfer fluid (HTF), storage technology and power conversion system. North–South and East–West orientations equipped with single tracking mechanism are usually applied in trough solar field [29]. For central receiver, surrounded and North field configurations are the most proven technologies, while MTC (Micro Tower Configuration) is now under development [46–50]. Whereas linear receivers are used for parabolic trough and Fresnel technologies, various configurations exist for power tower concept. These configurations, for some of them under design, test or improvement, include the volumetric receiver, the particle receiver and the cavity receiver [51–54]. Concerning heat transfer fluids (HTF), molten salt is widely used as HTF in commercial plants. Synthetic oil and saturated steam are also currently used as HTF's in commercial plants. Superheated steam has been recently introduced as HTF [55–59]. Pressurized air and other gases, in particular CO_2 and N_2, nano-fluids, concrete and circulating particles are under development for both trough and tower, while helium or hydrogen is used in dish Sterling [60–62].

Concerning storage, liquid molten salt is already proven storage medium for long time whereas steam is typically reserved for short time storage [63,64]. Phase change materials and compact heat storage (chemical reactions) are under development [63–65]. Power conversion systems (thermodynamic cycles)

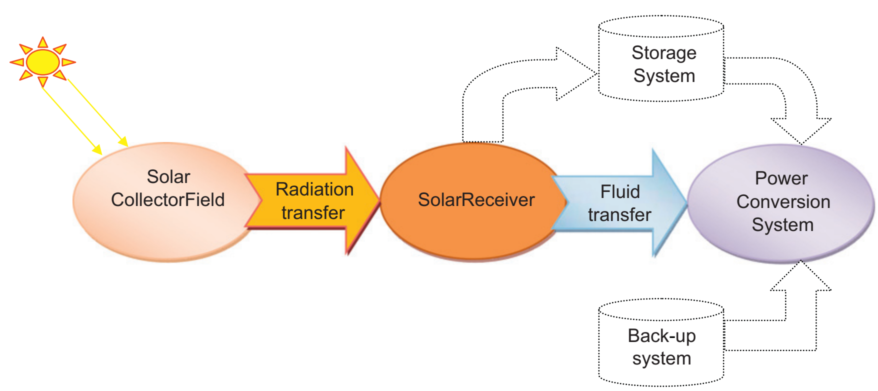

Fig. 4. Flow diagram for a typical CSP-plant.

Table 1
Comparison of the four CSP families.

CSP technology	Parabolic trough	Central receiver	Linear Fresnel	Dish
Solar collector [6]	Line focus	Point focus	Line focus	Point focus
Solar receiver [6]	Mobile	Fixed	Fixed	Mobile
Power conversion cycle	RC, CC	RC, BC, CC	RC	RC, SC
Concentration ratio [11]	70–80	> 1 000	> 60	> 1 300
Solar field slope (%) [11]	< 1–2	< 2–4	< 4	10 or more
Working temperature (°C)	Medium	Higher	Relatively lower	Highest
Current efficiency (%) [35]	15–16	16–17	08–10	20–25
Plant peak efficiency (%) [11]	14–20	23–35	18	30
Typical capacity (MW) [11,29]	10–300	10–200	10–200	0.01–0.025
Annual capacity factor (%)[11]	25–28 (without storage) 29–43 (with 7 h storage)	55 (with 10 h storage)	22–24 (without storage)	25–28 (without storage)
Development status [29,33]	Commercial proven	Commercial	Pilot project	Demonstration stage
Technology development risk [11,29]	Low	Medium	Medium	Medium
Outlook for improvements [6]	Limited	***Very significant***	Significant	Via mass production
Efficiency with improvements [33]	18	**25–28**	12	30
Relative rise of efficiency after improvements (%) [33]	20	**40–65**	25	25

are at present Rankine cycles (RC), Brayton cycles (BC), combined cycles (CC) for trough, tower and Fresnel types, and Stirling cycles (SC) for parabolic dish technology [42]. Advanced Brayton cycles with pressurized air heated by volumetric solar receiver are nowadays an important issue [3]. Furthermore, supercritical steam and carbon dioxide cycles, air Brayton cycles are well positioned and promise to enhance solar power tower technology [17,50,66].

2.1.3. Factors boosting CSP technology

Besides activities in R&D and test and prototyping, numerous supports in various forms of incentives are playing a major role in the development of power generation through CSP. Incentives in the form of feed-in-tariff, tax relief, capital cost grants encouraging electricity export rates for CSP-plants during recent years, in a lot of countries (Algeria, Egypt and Morocco in North Africa; Spain, Portugal, Italy and Greece in Europe; USA in North America; and India, China and Australia in Asia), has caused a rapid growth of these future power options. Likewise, other countries are in initiation phase or in the planning to set a favourable policy support for encouraging the development of CSP. [10–25]

Concepts such as Desertec, TRANS-SCP, MED-CSP, SolarPaces and ESTELA that aim to set up CSP technologies in EU-MENA regions are very promise to open the door for solar thermal power plants to be more competitive [4,5,67–69]. National and international organisations (Banks, Agencies…) support also the development of CSP. For instance, in 2000, the Global Environment Facility Bank (GEF) provided 50 million US$ grant for four CSP projects in India, Egypt, Morocco and Mexico. This grant is to be used to cover its incremental costs, and therefore support market introduction of hybrid configurations in developing countries [15].

The overall experience in CSP technology development has been positive and new opportunities are opening. At the R&D and demonstration level, many projects have been carried out. At the configurations and component development projects, one can name DISS, SOLAIR, EURODISH and ECOSTAR projects. SOLGATE, SOLASYS and SOLHYCO are among the projects that have been carried out for the hybrid concepts implementation. DISTOR is a project worth citing for storage systems development [70,71].

At the pilot and demonstration level, the projects PS10, PS20 and SOLAR TRES among others have provided valuable information for the development of the CSP technology. They have offered excellent pattern to move CSP technology forwards [17,71]. Building on this experience, new pilot projects are underway or in the planning stage (ALSOL in Algeria).

At the industrial and commercial plants of 50 MW to 400 MW power are underway or in operation in Spain, USA, Algeria, Egypt, Morocco, Mexico, Greece, Iran, India and China. The exploitations of these plants have been conclusive that there is a move to the deployment of large scale CSP plants [10–28]. Up to the year 2030, the market potential is estimated at least at 7 GW in the EU-MENA. This offers the opportunity to CO_2 reduction prospective of up to 12 million tons per year. These plants represent also a cost fall potential of 20% compared to the last built 80 MWe SEGS IX plant in USA. According to ECOSTAR, there are three main drivers for cost reduction: scaling up, volume production and technology innovations. About 50% of the intended reductions in costs of CSP-plants will be from technology developments, and the other half from scale up and volume production [71].

In this context solar thermal power plants will be capable of delivering efficiently more than 3% of the EU's electricity by 2020, and at least 10% by 2030 [67]. Moreover, it offers the opportunity to generate about 50% of the electricity needs of the EU-MENA region [4,5] and supply over 10% of the world's electricity by 2050 [6]. Advanced scenario by IEA, EU and DLR has anticipated that global CSP capacity will reach 1.5 TW at this year [4,6,11,33].

2.2. Central receiver system (CRS): Current status and applications

Of all CSP technologies available today the CRS is moving to the forefront and it might become the technology of choice [11,72]. This is mainly due to the expected performance improvements and cost reductions associated with technology innovations of the three main subsystems, i.e., the heliostat, the receiver and the power block within the near future. Compared with other CSP options, the central receiver system could not only provide cheaper electricity than trough and dish systems but also better performance [3,11]. As shown in Table 1, CRS offers:

- Higher temperatures (up to 1000 °C) and thus higher efficiency of the power conversion system [11,71];
- Easily integrated in fossil plants for hybrid operation in a wide variety of options (see Section 5.3) and has the potential for generating electricity with high annual capacity factors (from 0.40 to 0.80 [11]) through the use of thermal storage [11,29];
- Greater potential for costs reduction and efficiency improvements (40–65%) [11,29,71].

2.2.1. Basic concept

As shown in Figs. 5–7, a typical central receiver system, also known as a solar tower power, consists of three major subsystems, namely the heliostat field, the receiver and the power conversion system. The solar field consists of numerous computer-controlled mirrors that track the sun individually in two axes and reflect the solar radiation onto the receiver located on the top of the tower. The receiver absorbs the heliostat reflected solar radiation and converts it into heat at high temperature levels. Depending on the receiver design and the heat transfer fluid nature, the upper working temperatures can range

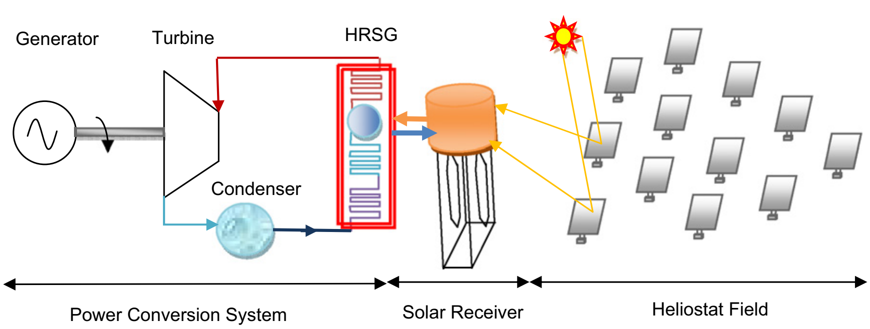

Fig. 5. The three main subsystems of central receiver solar thermal power plant.

Fig. 6. Examples of CRS power plants in operation, underway or in the planning; from Left to right. (A) PS10 PS20 (front) in operation nearby Seville, Spain [79]. (B) Ivanph plant under construction, 75% completion, CA, USA [32]. (C) Artist's design of Rio Mesa solar project (planned) [84].

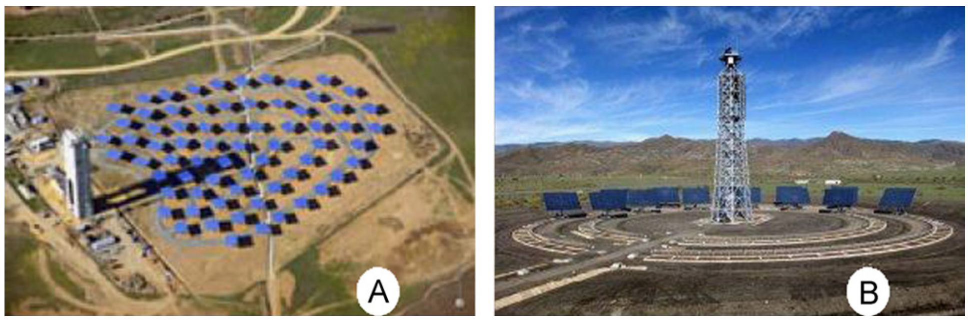

Fig. 7. Advanced research projects; from left to right. (A) SOLUGAS project at the Solucar Platform in Seville, Spain [32]. (B) Variable Geometry Central Receiver Solar Test Facility at CTAER [32].

from 250 °C to 1000 °C [11,71]. A power conversion system is used to shift thermal energy into electricity in the same way as conventional power plants [11,29].

The heliostat field is the main subsystem and its optical efficiency has a significant impact on the performance of the power plant; it represents about 50% of the total cost [73] and its annual energy losses are around 47% [74].The receivers are made up of material which withstands high temperature changes and high energy density such as ceramic and metal alloys. There are different types of receivers that can be classified into three groups depending on their functionality and geometric configurations. The three groups are the volumetric receivers, the cavity receivers and the particle receivers. In a power conversion system thermal energy can be converted into electricity with higher efficiency in Rankine cycle, Brayton cycle or combined cycle.

2.2.2. *Central receiver solar thermal pilot plants*

The tower technology has since the early 1980s attracted worldwide a lot of interest. It has then been thoroughly studied and successfully tested in numerous pilot projects such as the American Solar Two (upgrade Solar One) [3], the Spanish CESA 1 and TSA, and the French THEMIS [41,75,76]. The most relevant CRS tested in the 20th century are reported in Table 2. These demonstration power plants have proved the feasibility and the economical potential of the tower technology. They have also permitted the improvement in the design and performance of the tower power, mainly its components, its hybrid concepts, its heat transfer fluids and storage system.

Table 2
Central receiver solar thermal pilot plants in the 20th century [29,32,78–80].

Project acronym	Capacity MW	Country	Starting year
SSPS	0.5	Spain	1981
TSA	1	Spain	1993
CESA-1	1	Spain	1983
Solar one	10	USA	1982
MSEE/Cat B	1	USA	1984
Solar Two	10	USA	1996
THEMIS	2.5	France	1984
EURELIOS	1	Italy	1981
SUNSHINE	1	Japan	1981
SPP-5	5	Russia	1986

2.2.3. *Central receiver solar thermal power plants in operation [32,59,77–80]*

Concerning the heat transfer fluids (HTF), water/steam has initially been adopted in some solar towers such as PS10, PS20, Beijing Balading, Sierra and Yanqing. Molten salt is also a very commonly used HTF. It has been used for example in Gemasolar thermo-solar plant. Lately, there has been a big interest in developing air as a HTF. Jülich solar tower is an example of this case.

Depending on the receiver design and the heat transfer fluid, the working temperatures of the power conversion system range from 250 °C, for water/steam cycles, to around 600 °C with current molten salt design. The development of Direct Steam Generation (DSG), which is currently in its early stage, as HTF is very promising for reducing costs and enhancing thermal efficiency by eliminating the heat exchangers network [59,77].

In 2006, the 11 MWe CRS power plant PS10 was built by Abengoa Solar in Sevilla Spain. It has been followed by the 20 MWe power tower plants PS20 in the same location, the 5 MW Sierra Sun Tower (in Lancaster, USA) and the 1.5 MW in Jülich Germany in 2009. Since 2011, the Gemasolar power plant, built in Spain as large as the PS 20 power plant, but with surrounded heliostat field and15 h storage, has been operating and delivering power around the clock [77]. After the three pioneer CSP countries, i.e., the USA, Germany and Spain, China have entered the CSP market by implementing, in 2010, the Beijing Yanqing solar power plant. It has been then followed by Beijing Badaling Solar Tower in 2012.The most important central receiver power plants in operation throughout the world are reported in Table 3.

Table 3
Central receiver solar thermal power plants in operation [32,78–83].

Name	Country, location	Owners	Capacity (MW)	Break ground date	Starting year	Heliostat field area (m^2)	Receiver type	Power cycle	Storage	Type
Beijing Badaling	China Beijing	Academy of sciences	1.5	July 2009	August 2012	10,000	Cavity	Rankine	1 h	Fossil–solar
Gemasolar	Spain, Andalucía (Sevilla)	Torresol energy	19.9	February 2009	April 2011	304,750	Cavity	Rankine	15 h	Fossil–solar
Jülich	Germany, Jülich	DLR	1.5	July 31, 2007	December 2008	17,650	Volumetric	Rankine	1.5 h	Fossil–solar
Planta solar 10	Spain, Sanlúcar la mayor (Sevilla)	Abengoa solar	11.0	2005	June 25, 2007	75,000	Cavity	Rankine	1 h	Fossil–solar
Planta solar 20	Spain, sanlúcar la mayor (Sevilla)	Abengoa solar	20.0	2006	April 22, 2009	150,000	Cavity	Rankine	1 h	Fossil–solar
Sierra	United States lancaster California	eSolar	5.0	July 2008	July 2009	27,670	Cavity	Rankine	—	Solar only
Yanqing	China, yanqing county	Academy of sciences	1	2006	July 2011	10,000	Cavity	Rankine	Two-stage heat storage	—

(–) not available.

2.2.4. *Central receiver solar thermal power plants under construction [32,78–80]*

Nowadays many power tower projects are underway worldwide and most of them will be operational in 2013. In Spain, about 700 MW of CSP-plants are being commissioned this year. For the USA, a total of 1.2 GW CSP power installations are underway and should be in operation in 2013. Near San Bernardino County, California, the largest plant Ivanpah has reached around 75% completion. This power tower is the result of a close collaboration between BrightSource and the pioneer corporation Google. Africa is a very promising market for CSP. For example, near the Kaxu Solar One parabolic trough power station, the largest 50 MW Khi Solar One plant is under construction in South Africa. Details about underway solar towers are presented in Table 4.

Table 4
Central receiver solar thermal power plants underway [32,78–80].

Name	Capacity (MW)	Country location	Expected completion
Ivanpah facility (3 units)	377	USA, San Bernardino county, CA	2013
Crescent dunes	110	USA, Nye county, NV	2013/14
Khi solar one	100	South, Africa Upington	2014
Delingha	50	China, Delingha	2013
e-Cube 1	1	China, Hainan	2013
THEMIS	1.4	France, Pyrénées-Orientales	—

(–) not available.

2.2.5. *Central receiver solar thermal power plants in the planning [32,78–80,84]*

More than 10.135 GW CSP power installations are announced mainly by the USA and Spain but also by China [79]. Projects in the field are also under consideration in the Sun Belt countries such as Algeria, Morocco, Saudi Arabia and India [80]. Saudi Arabia has recently announced an enormous deployment of CSP technology in over the next 20 years, with a target of 25 GW by 2032 [32]. Table 5 illustrate the announced CRS to be operational before 2020 [32,79]. The main planned CRS power plants to be operational by 2020 are listed in Table 5. In the USA, a large part of the projects are for the 200–500 MW CRS power plants. For instance, BrightSource Energy has taken over the Palen Solar Power project after Solar Millennium bankruptcy in 2012. However, the concept is expected to switch from the parabolic trough technology to the CRS one.

The Palen project includes two 250 MW adjacent power plants similar to Ivanpah technology. Each plant is designed with about 85,000 heliostats for sunlight reflection to the receiver located on the top of a 228 m tower. Expected to be operational by June 2016, this project realisation is projected to start by the end of 2013. Likewise, BrightSource is developing another two 500 MW projects named Rio Mesa and Hidden Hills. These two projects are still in the certification process.

On the other hand, in Arizona, Crossroads Solar Energy Project that includes a 150 MW tower technology and a 65 MW solar photovoltaic (PV) technology is being developed by SolarReserve's. The Crossroads central receiver technology is a molten salt heat transfer fluid and storage medium technology. It is the same technology that has been adopted for the Crescent Dunes which is underway by the same company in Tonopah, Nevada. Intended to be operational two years after breaking ground, the power facilities are expected to supply more than 500 GW h per year of green electricity to Arizona or California.

2.3. *Recent R&D activities in central receiver technology*

Recent R&D activities in particular, ECOSTAR, have focused on the most important factors and actions that contribute significantly to achieve a cost reduction in tower concept. Scaling up and mass production can contribute to about 50% in LEC reduction, while the other half in LEC reduction is the result of R&D efforts, according to these studies [11,29,71].

The ECOSTAR study pointed out that the lowest LEC for large scale CSP-plants would be for solar tower concept with pressurized air and molten salt technology [71]. These results are confirmed by latest studies [40].

Over the last decade, R&D efforts have been growing sharply in the USA (SNL, NREL) and the Europe (DLR and CIEMAT); China, India and Australia are starting momentous R&D activities, while other developing countries have expressed interest, in particular Algeria, Morocco and UEA [10–28,32,80,85]. Progress in R&D, and so, performance improvements of the three major components can achieve very significant costs reduction [3,7,8,11,71].

After a stagnation period that extended from 1996 to 2000, several R&D projects have been launched mainly in Europe and the USA to investigate the solar tower technology under real solar conditions. As a result, many pilot plants have been erected and their O&M methods

Table 5
Planned Central receiver solar thermal power plants [32,78–80].

Name	Country	Capacity (MW)	Location
Rio mesa solar project	USA	500	Riverside county, California
BrightSource PPA5	USA	200	Mojave, California
BrightSource PPA6	USA	200	Mojave, California
BrightSource PPA7	USA	200	Mojave, California
Rice solar energy project	USA	150	Riverside County, California
Crossroads solar energy project	USA	150	Maricopa County, Arizona
Suntower	USA	92	Doña Ana County, New Mexico
eSolar 1	USA	84	Los Angeles County, California
eSolar 2	USA	66	Los Angeles County, California
AZ 20	Spain	50	Sevilla
Alcázar Solar Thermal Power Project	Spain	50	Alcázar de San Juan
Almaden Plant	Spain	20	Albacete
Unknown	China	2000	Mongolian desert, China

Table 6
Recent and announced R&D projects of CRS.

Research project	Country	Location	Main Developer	HTF	Budget	Main subsystem focus
ConSolar [29,86,70]	Israel	Israel	WIS	Pressurized air	—	Volumetric receiver hybrid Brayton cycle
SOLAIR [70]	Spain	Almeria	DLR, SIEMAT	Air	€3.3 million	Volumetric receiver
SOLHYCO [70]	EU+ Algeria	Spain	DLR	Pressurized air	€3,088,218	Hybrid Brayton cycle cogeneration
SOLASYS [70]	EU	Israel	DLR	Pressurized air	€2,536,077	Syngas hybrid Brayton cycle
SOLGATE [29,70,87]	EU	Spain	ORMAT	Pressurized air	€3.2 million	Volumetric receiver hybrid Brayton cycle
SOLUGAS [29,32]	Spain	Seville	Abengoa	Pressurized air	€6 million	Receiver Heliostat field
EU-SOLARIS [32]	EU	EU	CTAER	Various	€4,45 M	The three main subsystems
Variable geometry test facility [32]	Spain	Tabernas, Almeria	CTAER	Various	€5 million	Advanced concepts
Particle receiver integrated with a fluidized [32]	USA	USA	NREL	Gas/solid, two-phase flow	\$3.8 million	Particle receiver
Temperature falling-particle receiver [32]	USA	USA	SNL and DLR	Recirculation Particles	\$4.4 Million	Particle receiver
Small-particle solar receiver for high-temperature Brayton power cycles [32]	USA	USA	San Diego State University (SDSU)	Air a and carbon particles	\$3.8 millions	Particle receiver Brayton cycle
10 MW s-CO_2 turbine[32]	USA	USA	NREL	CO_2	\$8 million	Brayton cycle
s-CO_2 turbo-expander and heat exchangers [32]	USA	USA	Southwest research institute (SWRI)	CO_2	\$6.8 million	Power conversion cycle
New solar receiver that uses s-CO2 as transfer fluid [32]	USA	USA	Brayton energy LLC	CO_2	—	Particle receiver Brayton cycle
Molten salts loop test facility [32,85]	USA	Albuquerque, New Mexico	SNL	Molten salt	—	HTF

(–) not available.

and components optimized. With special focus on the hybrid configurations and with the aim of developing the three main subsystems of the central receiver concept, ConSolar, Solair and Solgate have confirmed the viability of the full-scale application of central receiver technology [70].

More recently, the US department of Energy has announced the SunShot program. In order to achieve significant costs reduction and to develop some innovative concepts such as the use of supercritical CO_2 as heat transfer fluid for Brayton cycle plants or falling particle receiver [32]. More than 21 R&D projects (totaling \$56 million over three years) have been launched. In order to enhance the falling particle receiver technology performance and reduce costs, four important R&D projects in the field have been awarded to NREL, SNL, Brayton Energy LLC and the University of Colorado. These R&D projects are outlined in Tables 6–10.

Likewise, Sandia National Laboratories (SNL) has announced the commissioning of its Molten Salt Test Loop (MSTL) at National Solar Test Facility (NSTF) in Albuquerque, New Mexico. The MSTL consists of 3 parallel test platforms with 38 t of melting salts. The tests have been successively meeting, or even exceeding all of the design requirements in plant-like conditions by achieving temperature range of 300–585 °C. [32,85]

In Europe, besides the pioneering Solar Platform of Almeria, an innovative research project named the Variable Geometry Central Receiver Solar Test Facility has been launched by the Spanish research center CTAER (Advanced Technology Center for Renewable Energy). In this demonstration plant, the heliostats are replaced by the so-called helio-mobiles. These helio-mobiles are placed over a mobile platform which moves over rails around the tower. The receiver, located at the top of a fixed tower, is housed in a rotating platform [32,88].

In order to demonstrate the feasibility and examine the thermal performance of a CRS- hybrid Brayton cycle plants, Abengoa have been built a SOLUGAS facility at the Solucar Platform in Seville,

Table 7
Expected improvements for the three main subsystems of CRS [33,71,93].

Heliostats field		**Solar receiver**		**Power conversion system**	
Enhancements	*Benefits (%)*	*Enhancements*	*Benefits (%)*	*Enhancements*	*Benefits (%)*
Heliostat and layout	Efficiency: +3 [93] Cost reduction: 17–26 [93] LEC reduction: 9–17 [71]	Multi-tower configuration	Efficiency: +5 [93] Cost reduction: 25 [93] LEC reduction: 1–7 [71]	Central receiver- Brayton cycle system (up to 50 MW) Central receiver-rankine cycle system (current Efficiency)	LEC reduction: 3–9 [71] Cost reduction: 17–29 [33] Supercritical: 22–26 [33] Superheated: 16–17 [33]
Tracking system	Cost reduction: 40 [93]	Higher operating temperature	Efficiency: 40–60 [93] LEC reduction: 1–7 [71]	Central receiver -combined cycle system	Cost reduction: 17–28 [71] LEC reduction: 3–14 [71]

Table 8
Heliostat field design data of operational solar power towers [32,78–86].

Name/Type	**Latitude, longitude**	**Solar radiation (kW h/m^2/yr)**	**Land area**	**Field area (m^2)/ Type**	**Area-N of Helios**	**Heliostat manufacturer**	**Heliostat Design**
Beijing Badaling solar tower/ demonstration	40°40′ North, 115°90′ East	1290	13 acres	100,000 North field	100 m^2 $N=100$	Himin solar	64 facets, each facet 1.25 × 1.25 m2
Gemasolar thermosolar plant/ commercial	37°33′ North, 5°19′ West	2172	195 ha	304,750 surrounded	120.0 m^2 $N=2,650$	Sener	Sheet metal stamped facet
Jülich solar tower/ demonstration	Rhineland	902	17 ha	17,650 North field	8.2 m^2 $N=2,153$	—	—
Planta solar 10/commercial	37°26′ North, 6°14′ West	2012	55 ha	75,000 North field	120.0 m^2 $N=624$	Abengoa	Solucar 120: Glass-metal
Planta solar 20/ commercial	37°26′ North, 6°14′ West	2012	80 ha	150,000 North field	120.0 m^2 $N=1,255$	Abengoa	Solucar 120: Glass-metal
Sierra suntower/ demonstration	34°46′ North, 118°8′ West	2629	—	27,670	1.136 m^2 N=24,360	eSolar	—
Yanqing solar power/ demonstration	40°40′ North 115°40′ West	—	208 acres	10,000	100 m^2 N=100	Himin solar	—

(–) not available.

Table 9
Solar receiver data of operational solar power towers [32,78–86].

Name	**Tower height**	**Receiver manufacturer**	**Receiver type**	**HTF**	**Inlet temp. (°C)**	**Outlet Temp. (°C)**
Beijing Badaling	118 m	Dongfang Boiler Group Co.,Ltd	Cavity	Water/Steam	104	400
Gemasolar	140 m	Sener	Cavity	Molten salts	290	565
Jülich	60 m	Kraftanlagen München	Volumetric	Air	80–100	680
Planta solar 10	115 m	Tecnicas reunidas	Cavity	Water/ steam	—	250–300
Planta solar 20	165 m	Tecnicas reunidas	Cavity	Water/ steam	—	250–300
Sierra	55 m	Babcock & Wilcox victory energy	Dual-cavity receiver & tubular external	Water	218	440
Yanqing	100 m	—	Cavity	Superheating steam	—	390

Table 10
Power conversion cycle design of operational solar power towers [32,78–86].

Name	**Turbine capacity gross/net**	**Turbine manufacturer**	**Power cycle**	**Cooling system**	**Fossil back-up**	**Thermal storage**
Beijing Badaling	1.5 MW/1.5 MW	Hangzhou steam turbine	Steam rankine 400 °C,4 MPa	Wet cooling	Oil-fired boiler	Two stages; saturated steam/oil
Gemasolar	19.9 MW/19.9 MW	Siemens	SST-600 2-cylinder Reheat steam turbine	Wet cooling	Natural gas	Tow tank; Molten salt
Jülich	1.5 MW/1.5 MW	Siemens	Steam Rankine 480 °C, 26bar	Dry cooling	—	Ceramic heat sink
Planta solar 10	11.02 MW/11.0 MW	GE	Steam Rankine 40 bar 250 °C, 2 Pressures	Wet cooling, refrigeration towers	Natural gas	—
Planta solar 20	20.0 MW/20.0 MW	GE	Steam Rankine 45.0 bar	Wet cooling, Refrigeration towers	Natural gas	—
Sierra	5.0 MW/5.0 MW	—	Steam Rankine	Wet cooling, Cooling towers	—	None
Yanqing	1 MW/1 MW	—	Steam Rankine 2.35 MPa	—	—	two-stage heat storage system

(–) not available.

(–) not available.

Spain. The R&D plant consists of a modified gas turbine located close to a 35° inclined receiver collecting solar radiation reflected by a 69 heliostat field. It has been a truly close collaboration between all of the participants with DLR, Turbomach, GEA Technika Cielpina, New Energy Algeria being the developers and Abengoa the constructor [32,89–91].

Another important European project is EU-SOLARIS, the European CSP research Mega-facility. The project is very promising. In addition to ESTELA, Germany, Spain, Greece, Italy, France, Cyprus, Portugal, Turkey and Israel are collaborating in this project [32,92].

The following sections review the most important R&D activities and published papers on the major components of the central receiver solar thermal power plants. The R&D studies and their results are reported and classified into three groups according to the subject treated, namely heliostat field, solar receiver and power conversion system. In each group the analysis of existing design, experiments and suggested development and expected improvements are presented in order to make the article more helpful for future research.

3. Heliostat field

The performance of CRS depends strongly on the solar field efficiency which in its turn is related to the heliostat design, the field layout, the tracking system and control system. In this section, the published studies focused on the heliostat field are reviewed and their results are briefly reported. Also, methods and techniques used or proposed for enhancing the heliostat and the heliostats field performance are sketched out.

3.1. Heliostat and layout

3.1.1. Basic concept

The solar field consists of a large number of tracking mirrors, called heliostats. A single heliostat includes a set of mirrors, a tracking system, a frame, a structure foundation and control system. The basic design of single heliostat is illustrated in Figs. 8–17. Heliostat field performance is a function of the optical efficiency. Cosine effect, shadowing effect, blocking effect, mirror reflectivity, atmospheric attenuation, and receiver spillage are the main factors affecting a heliostat optical efficiency [29]. It is well known that the half of the total investment cost and 40% of total energy losses are attributed to the heliostat field. It is then essential to optimize its design to reduce the capital cost and to improve the overall efficiency of the power plant [36,29].

3.1.2. Design

Siala and Elayeb [94] have presented the mathematical modeling of a graphical method for no-blocking radial stagger heliostats layout. In the proposed method, the field is divided into certain groups of heliostats to increase its density and the Authors reported that the method is simple compared to cell-wise procedure.

For positioning the heliostats, Sańchez and Romero [95] have proposed a new procedure, named Yearly Normalized Energy Surface (YNES). In this method, the heliostats positioning is determined using the yearly direct solar radiation available at any location. The inferred results agree closely with that that of WinDelsol and SOLVER codes; nevertheless, the annual optical efficiency needs to be calculated by ray tracing method, and thus, the procedure is time consuming.

Wei et al. [96] have coupled the ray tracing technique with the parametric search algorithm to estimate the optical efficiency and to optimise the heliostat field layout. Using this method they have investigated four different layout types, i.e., North–South cornfield, North–South stagger, Radial cornfield and Radial staggered, and found that North–South cornfield layout is the most suitable for 1 MWe solar tower power plant in China.

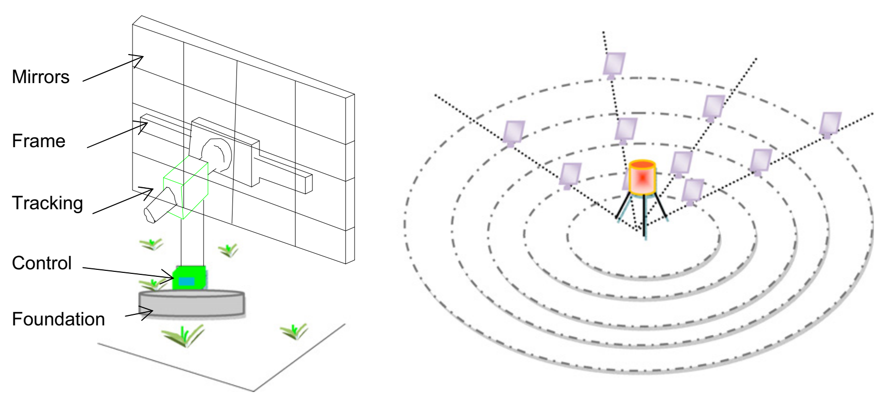

Fig. 8. Basic concept of heliostat (left); radial staggered layout for positioning heliostats (right).

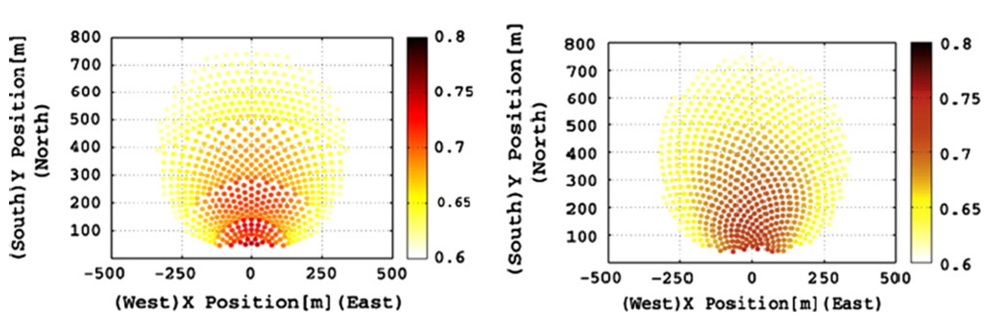

Fig. 9. Field density and optical efficiency of radially staggered layout (left) and phyllotaxis spiral layout (right). Spiral layout respectively enhances optical efficiency and reduces land area by 0.36% and 15.8%, compared with radial layout [112].

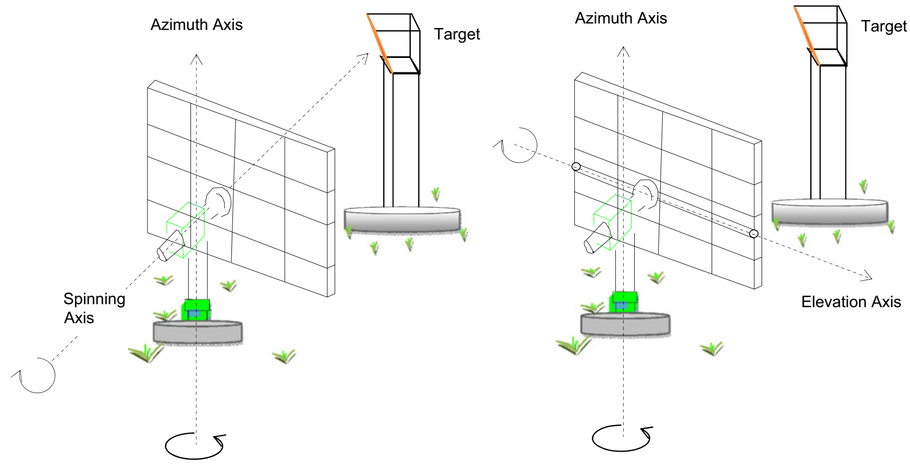

Fig. 10. Spinning—elevation (left) and Azimuth—elevation (right) tracking methods.

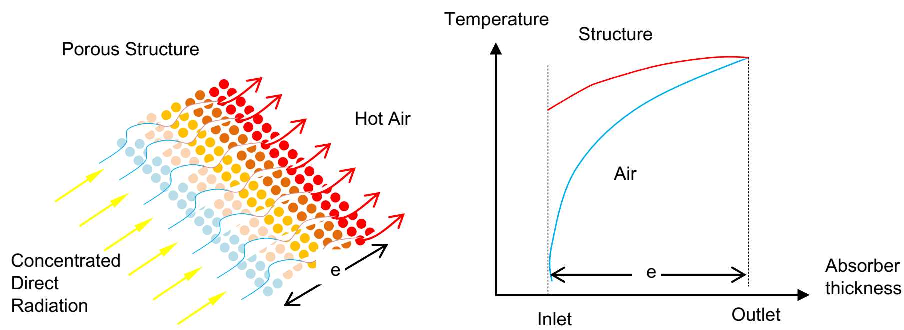

Fig. 11. Volumetric effect of volumetric receiver.

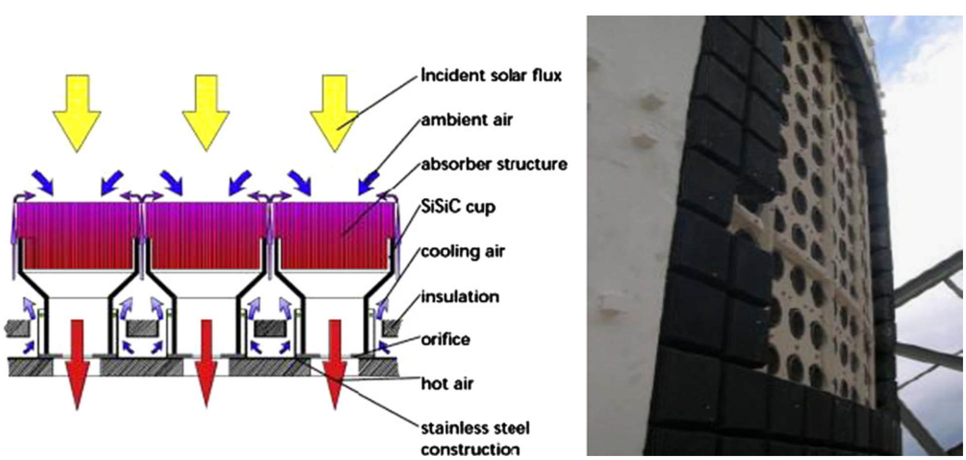

Fig. 12. Volumetric receiver used in HiTRec and Solair projects (left), solar receiver at PSA (right) [53] (experiments).

Wei et al. [97] have developed a new method and a faster code called HFLD (Heliostat Field Layout Design) for heliostats layout. In this method the heliostat field optimization is based on the receiver geometrical aperture and an efficiency factor. Applying their technique to the PS10 power plant, they proposed a new layout for PS10 field as good as that is already implanted. Furthermore; the Authors introduced a new methodology based on sunshine duration to investigate the possibility of framing under heliostats.

Wei et al. [98] have detailed the mathematical formulations of tracking and ray tracing techniques for the target-aligned heliostat. To this end they have created and incorporated in the HFLD code a new module to analysis such heliostat with asymmetric surface and compared the simulated results with the well known software Zemax with good agreement.

Wei et al. [99] have implemented in the HFLD code a module for design and analyze of aspherical toroidal heliostat field. They found that the toroidal heliostat field has higher performance than that of spherical heliostat if the design and tracking system are ideal. They have also recommended the selection of crop according to the distribution map of the sunshine duration when framing under heliostats.

Wei et al. have developed and incorporated into the HFLD code a new module for the beam-down central receiver system based

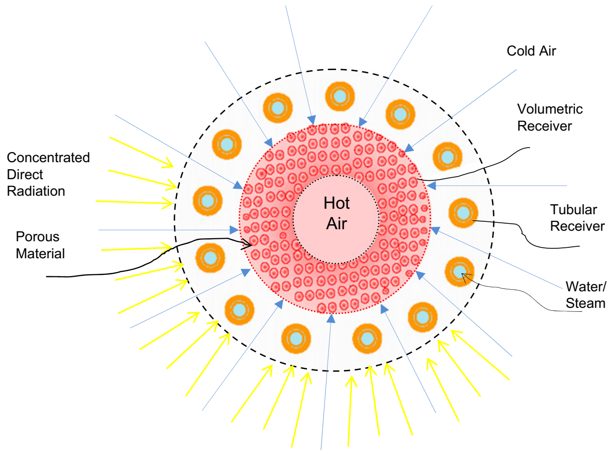

Fig. 13. Top view of dual volumetric-tubular receiver (suggested enhancement).

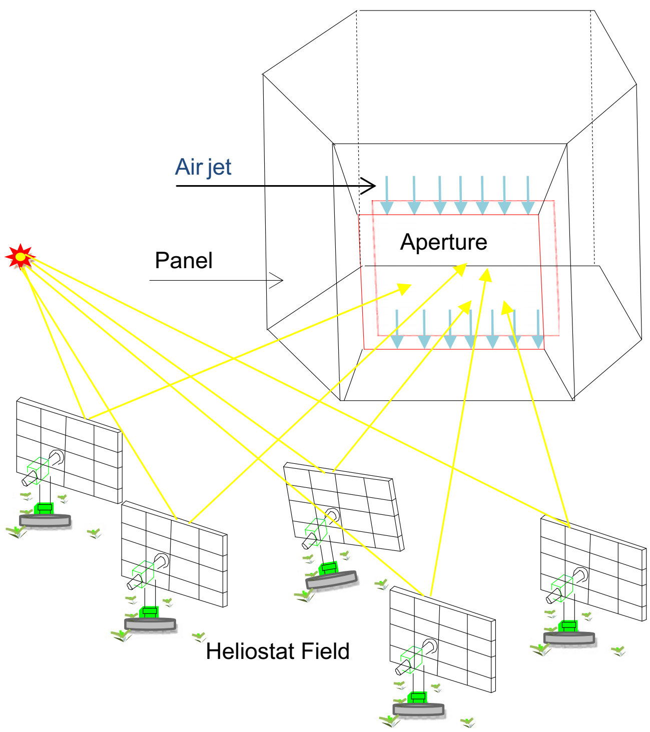

Fig. 14. Basic design of a cavity receiver made of five panels, an aperture and an aerowindow for the protection.

on the ray tracing method. The selected power plant for the study has consisted of 3 heliostats and a hyperboloid reflector. They have found good agreement between their results and that obtained by the well-known software Zemax. [100]

Zhang et al. [101] have defined a new factor named available land efficiency. This factor is function of the cosine effect, atmospheric attenuation and the intercept efficiency. It has been used to position in an optimum way the heliostats of 1 MW solar tower power plant and found that their technique grants an annual efficiency of 71.36% when incorporated in the HFLD code.

Augsburger and Favrat [102] have studied the thermoeconomic of heliostat field to find design parameters of solar tower power plant that offers better performance, in particular, efficiency, investment costs and environmental benefits.

Collado [103] has developed a simplified model to be used for preliminary studies of surrounding heliostat field and successfully compared its performance to Solar Tres demonstration plant data.

Utamura et al. [104] have proposed a methodology to get an optimal layout of group of heliostats in beam-down central receiver. They found that, due to spillage effect, the optical losses become significant at heliostats located at a distance from the tower farther than four times the tower height.

Wang and Wei have proposed a layout of 100 heliostats for 1 MW solar tower power plant in China. [105]

López-Martinez et al. [106] have predicted the cloud passage by computing heliostat field cover factor. They have suggested turning off some heliostats to bring down the receiver temperature before the cloud covers, and therefore, prevent the receiver from thermal stress.

3.1.3. Experiment

Wang et al. [107] have experimentally measured the effects of wind on a 100 m^2 area Dahan heliostat under various operating conditions of vertical and horizontal wind direction. They have found that the maximum wind pressure at each test point and blockage is obtained in the wind speed of 14 m/s. This latter have been used to estimate the maximum displacement and strain of the heliostat structure.

Chen et al. [108] have designed, constructed and tested the first prototype of a 4 m^2 non-imaging focusing heliostat. They have reported that a solar furnace system using this prototype has successfully reached in access of 3400 °C.

Schell [109] has reported the design, the realisation, the testing-calibration, and performances measurement of esolar heliostat fields which focuses on low-cost design, high-volume manufacturing and ease of installation.

Fernández-Reche [110] has carried out a statistical analysis of the reflectance in the heliostat field at the Plataforma Solar de

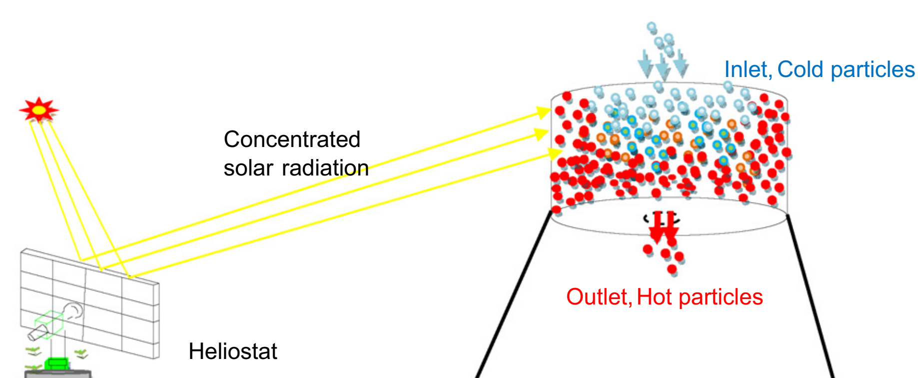

Fig. 15. Basic concept of solid particle receiver; a cylindrical receiver where particles are injected from the top-center to be heated up and returned from the bottom.

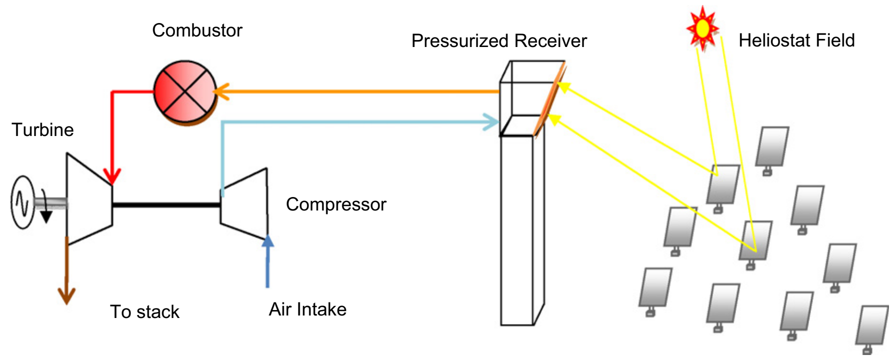

Fig. 16. Solar central receiver Brayton cycle (SCR-BC) system.

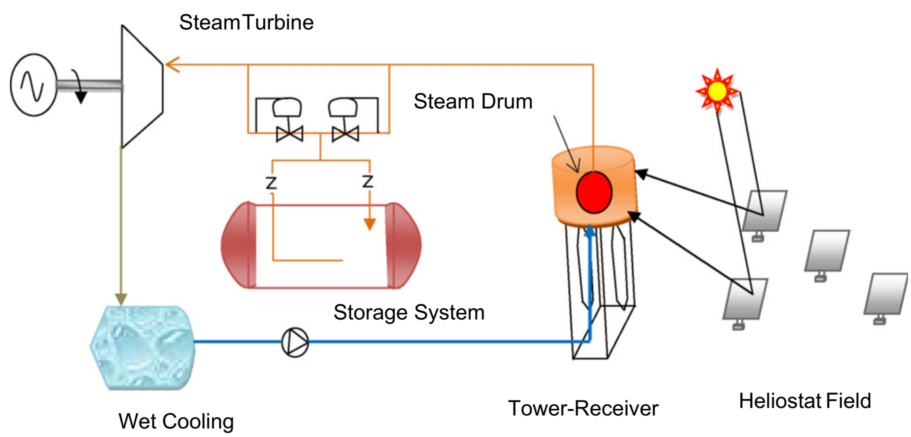

Fig. 17. Solar power tower with saturated steam cavity receiver and storage system (PS 10-like plant).

Almeria (PSA) in order to determine find the minimum number of measurements necessary to provide a total reflectance and pointed out that the methodology is useful in other solar thermal systems such as parabolic trough and dish collectors.

Collado [111] has examined the accuracy of UNIZAR and HFCAL analytic flux density models by comparing their performance to measured flux densities sent by 10 off-axis aligned heliostats onto a vertical receiver plane at PSA. They concluded that both HFCAL and UNIZAR are efficient tools to simulate the energetic images from heliostats, although the UNIZAR is less simple and slightly less accurate than the former HFCAL.

3.1.4. *Enhancement*

Noone et al. [112] have proposed a new pollytaxis spiral field layout based on heliostats discretization approach. They have compared the results of the proposed layout approach with current PS10 field arranged in a radially staggered configuration, as well as, with the simulated results of Wei et al. [97]. They concluded that the spiral layout allow placing heliostats in high efficiency field positions, and thus, offers higher optical efficiency and significantly reduce land area and Levelized Energy Cost LEC.

Leonardi and Aguanno [113] have developed a code named CRS4-2 to evaluate the optical performance of solar field made up of both square and circular heliostats of diverse geometrical parameters. They have then introduced a new factor called the characteristic function that depends on the zenith and the azimuth angles. This factor has been applied to estimate the total energy collected by the field; while the shading-blocking effects have been determined by a tessellation of the heliostats. In addition to the comparisons of concentrating solar thermal systems, the code going to be extended to the analysis of Multi-Tower configuration, Beam-Down and Multi-Apertures concepts.

Danielli et al. [114] have introduced a new concept named Concatenated Micro-Tower CMT. They have compared its performance with that of larger configuration and have revealed that CMT with a dynamic receiver allocation can improve the annual optical efficiency by 12–19%.

Pitz-Paal et al. [115] have coupled genetic algorithm with Nelder–Mead algorithm to design heliostat field for high temperature thermo-chemical processes for fuels production. They have found that the selected chemical process has a strong impact on the field design and performance.

Collado [116] has developed a simplified radial staggered method for surrounded heliostat field that uses only two parameters for the optimisation, i.e., a blocking factor and an additional security distance, required for installation and maintenance. He has confirmed that the Houston cell-wise method (UHC-RCELL) needs some improvements to find optimum mean radial and azimuth spacing of the heliostat field.

Collado and Guallar have partially described a new code, called campo. This code is meant to be used to solve the complex problem of the optimized design of heliostat field layouts, by performing accurate evaluation of the shadowing and blocking factor for heliostats placed in radial staggered configuration. They have compared the resulting optimized layout to that of the Gemasolar plant with good agreement. [117]

Chen et al. [118] have developed and constructed a second generation of non-imaging heliostat, which is three times larger than the first generation. They have then applied the new heliostat prototype for potato peeling and results have been very promising.

Vázquez [119] has analyzed the mechanical structure and tracking of SENER heliostat. He has been developed the SENSOL code that could be used for design of heliostat structure taking into account the wind loads, and proposed a new lighter design for SENER heliostat equipped with cheaper tracking system.

Augsburger and Favrat [120] have focused on the effects of cloud passage, over of the heliostat field, on the receiver flux distribution. They have then proposed a strategy for the progressive start-up/shut-down of the heliostats to ensure regular transients. The study is applied to the case of a Gemasolar-like circular heliostat field with a cylindrical receiver.

Ballestrin and Marzo [122] have been interested in the solar radiation attenuation loss between the heliostats and the receiver. They have compared the results of three simulation software, i.e., MODTRAN, DELSOL and MIRVAL, to that obtained by the Pitman and Vant–Hull model [121]. They have considered two atmosphere types, i.e., the rural atmosphere (visibility 23 km) and poor atmosphere (visibility 5 km), and concluded that the MODTRAN software is more accurate and more versatile than the DELSOL and the MIRVAL under various climate types.

3.2. Tracking and control system

3.2.1. Basic concept

In the solar field, each heliostat tracks the sun to minimize the cosine effect, and therefore maximize the solar energy collection through positioning its surface normal to the bisection of the angle subtended by sun and the solar receiver. Heliostat sun tracking can be classified either as Open loop system or as closed loop system [14]. The open loop system is based on astronomic formulae relating the sun's position to the system geometry. This system is reliable-low cost and it is recommended for larger solar field because the heliostat is under computer control. On the other hand, the closed loop system uses sensor to track the sun. This system is then more accurate and very useful for small heliostat fields. However, this system suffers from lower performance during cloudy period. Two sun-tracking methods are usually applied in CRS, i.e., the Azimuth–Elevation (A–E) and Spinning–Elevation (S–E) [28]. Compared with A–E the S–E tracking method allows more solar energy collection at the receiver and reduces spillage losses by 10–30% [28].

3.2.2. Design

Chen et al. [123] have analyzed the optical performance of two different sun tracking methods at the level of a single heliostat and at that of a heliostat field. They have been considered the case of a fixed geometry non-imaging focusing heliostat using Spinning–Elevation (S–E) axis and the case of a spherical geometry heliostat using Azimuth–Elevation (A–E) axis are considered. They have found that the S–E tracking system can reduce the receiver spillage losses by 10–30%; moreover, the S–E tracking provides much more uniform concentrated sunlight at the receiver without huge variations with the time of day compared to the A–E system.

Chong and Tan [124] have detailed in a comparative study on the range of motion of an A–E and an S–E tracking systems for both single heliostat and heliostat field. They have concluded that the annual power consumption of S–E tracking method is lower than A–E method.

Chen et al. [125] have derived a new sun tracking formulas for a non-imaging focusing heliostat that has no fixed optical geometry based on the non-imaging optical concept to focus the direct solar irradiation on the receiver.

Liang et al. [126] have proposed an open loop control system for heliostat tracking based on astronomic formulae to calculate the solar zenith and azimuth angles with a 0.052 mrad precision, taking into consideration the errors occurring during the heliostat's installation.

Badescu [127] has investigated the heliostat tracking error distribution of concentrated solar radiation on the receiver. He has compared the obtained results with the measurements data of Kosuke Aiuchi et al. [131]. He has deduced that some empirical probability distributions models such as Gaussian and the Uniform Distribution Approaches have many advantages in practice.

Jones et al. [128] have developed the so-called V-shot measurement system for measuring the local slopes of a heliostat mirror by scanning it with a laser beam, detecting the point of incidence of the reflected beam and calculating the resulting surface normal.

Chen et al. [129] have reported the algorithm and the methodology of residual aberration analysis of non-imaging focusing heliostat.

Moeller et al. have presented a control strategy for the detection of cloud passage. The control system turns the heliostats to standby position, and then returns them automatically to their original orientation after could passage [130].

3.2.3. Experiment

Aiuchi et al. [131] have designed, constructed and tested the accuracy of a photo-sensor sun tracking system for controlling heliostat using an equatorial mount in addition to two Aided-sensors to maintain stable tracking in a cloudy sky. They have achieved sun-tracking with an error of 0.6 mrad in clear weather. Nevertheless, the error is larger during cloudy periods and hence the larger are the energy losses.

Kribus et al. [132] have tested, at the Weizmann Institute heliostat field, a closed loop control system. This control system automatically corrects the tracking error though a dynamic measurement of spillage, detection of aiming errors, and feedback of a correction signal to the tracking algorithm that can reach the precision of 0.1 mrad.

Ulmer et al. [133] have designed, implemented and tested, at CESA-1 heliostat field, an automatic measurements system of heliostat slope deviation which based on the reflection of regular patterns in the mirror surface and their distortions due to mirror surface errors. The method offers significant gain in speed and handling and provides better predictions of the heliostat field performance with high resolution of about 1 million points per heliostat and measurement time of 1 min/heliostat. Furthermore, it can be used to measure other solar concentrators such as dish and parabolic trough.

3.2.4. Enhancement

Arqueros et al. [134] have suggested the use of star reflection on the mirror at night to move the heliostat in order to get enough information for determining the local surface normal at various points on the reflector.

Berenguel et al. [135] have used artificial vision technique and a B/W CCD camera to correct and control heliostat positioning offset in an automatic way. The proposed control system allows the elimination of the manual regulation.

Mehrabian and Aseman [136] have developed a computer programming algorithm for evaluating the typical angles of individual heliostats. The algorithm can be used for open loop control and to predict blocking and shading effect of the heliostat field.

Bonilla et al. [137] have coupled the hybrid heliostat field model and a wrapped model to handles the real-time simulation and communication between the heliostat field simulator and

Heliostat Field Control software HelFiCo. The Authors has also reported some techniques to improve simulation performance.

Roca et al. [138] have designed, simulated and tested an automatic controller that employs the mean hydrogen reactor temperature as feedback and selects the heliostats to be focused or taken out of focus, to make the CRS-hydrogen reactor within the margins of safety and for eliminating the manual control of heliostats. The ensuing experimental results of Hydrosol facility at CIEMAT–PSA have been very promising.

4. Solar receiver

In a CRS, the solar receiver is the heat exchanger where the solar radiation is absorbed and transformed into thermal energy useful in power conversion systems. There are different classification criteria for solar receivers, depending on the geometrical configuration and the absorber materials used to transfer the energy to the working fluid. In this survey, receivers are classified into three groups widely employed in central receiver system, i.e., volumetric receivers, cavity receivers and particle receivers. The results of numerous articles concerned with receivers design, experiments and improvements are presented in this part.

4.1. Volumetric receiver

4.1.1. Basic concept

Volumetric receivers consist of porous wires or either metal or ceramic. A good volumetric receiver produces the so-called volumetric effect, which means that the irradiated side of the absorber is at a lower temperature than the medium leaving the absorber [29]. The porous structure acts as convective heat exchanger where the HTF (in particular air) is forced to absorb the direct solar irradiation by convection heat transfer mode [29].

4.1.2. Design

Avila-Marın [53] has presented a detailed review of more than twenty volumetric receivers including their design, material and performance and then classified them into four groups based on air pressure and type of material: two open-loop receiver groups (Phoebus-TSA and SOLAIR), and two closed-loop receiver groups (DIAPR and REFOS).

Sani et al. [139] have investigated the use of ceramic zirconium carbide samples as absorbers in solar power plants. They have concluded that ZrC-based ultrahigh temperature ceramics has lower emissivity than SiC already used in volumetric solar receiver.

Kribus et al. [140] have dealt with unstable gas flow in volumetric receiver to find out overheating regions that cause local failures such as melting or cracking.

Becker et al. [141] have studied theoretically and numerically the flow behaviour in porous material and indicated that volumetric receivers with a high heat conductivity, a quadratic pressure drop and high ratio of viscous permeability coefficient to inertial permeability coefficient lead to stable flow.

Marcos et al. [142] have studied the effect of geometrical parameters on the Air Return Ratio ARR in volumetric receiver and obtained a higher average value of 70%. They have concluded that further improvements in design should take into account receiver edge, lateral wind and air injection angle.

Villafán-Vidales [143] has numerically analysed the heat transfer into volumetric receiver made of porous ceramic foam and applied in a thermo-chemical solar reactor for hydrogen production. He has validated the simulated results with experimental data of a reactor tested at a solar furnace. The Author has also reported that the receiver length has a weak influence on the temperature distribution of the fluid and solid phases. Moreover, he has found that the foam cell size does not affect considerably foam and fluid temperature distributions.

Wu [145] has developed a steady state macroscopic model for temperature distribution in a ceramic foam volumetric receiver. He has examined the effect of numerous design parameters and material proprieties on the temperature distribution of the fluid and solid phases by comparison to experimental data of [144]. He has concluded that the heat flux is strongly related to fluid media and appropriate distribution is obtained for thin ceramic foam sizes of 1–3 mm.

He et al. [148] have introduced a new method and unified Monte Carlo Ray-Trace (MCRT) code for calculating the solar energy flux density distribution in volumetric solar receiver with secondary concentrator. They have applied the proposed method to predict photo-thermal conversion process of solar energy. They have then found an error of 10% when comparing the numerical results with the measured data and the simulation results of Buck et al. [146,147].

Wu [150] has numerically investigated the convective heat transfer coefficient between the air flow and porous ceramic foam in volumetric receiver. He has proposed a new correlation as a function of cell size valid for porosity in the range of $0.66 < e < 0.93$ and Reynolds number in the range $70 < Re < 800$. His results were in good agreement with the experimental data of Younis et al. [149].

Fricker [151] has proposed a thermal storage system to protect solar receiver during transient conditions by feeding hot heat transfer fluid into the receiver when quick change in radiation intensity occurs.

4.1.3. Experiment

Sciti et al. [152] have conducted experiments to examine the potential of Ceramics, hafnium and zirconium diborides when used in high-temperature solar receivers. They have measured the room-temperature hemi- spherical reflectance spectra from the ultraviolet (UV) to the mid- infrared (MIR) wavelength regions. They have concluded that diboride family has a very high solar absorber performance because of higher absorbance over emittance ratio compared with SiC.

Fend et al. [144] have made comparative studies between the thermo-physical and heat transfer properties of six porous materials used in volumetric solar receivers. They have concluded that combining materials of high specific surface and porosity with good thermal conductivity (eg. SiC catalyst carrier) improves receiver performance although ceramic-based materials ~~are~~ are still offers better solution.

Fend et al. [153] have analyzed two high porosity materials that are suitable for volumetric receivers. The metal foam of different cell density has been investigated. The obtained results have shown that double layer silicon carbide metal foam has better performance than single layer.

Albanakis et al. [154] have experimentally compared the heat transfer and pressure drop of nickel and inconel metal foams when used as volumetric solar receiver and revealed that the pressure drop and the heat transfer of nickel foam are higher than those of inconel metal.

Wu et al. [155] have experimentally and numerically investigated the pressure drop in ceramic foam employed in volumetric receiver considering ten sorts of ceramic foam structures. They have derived a new pressure drop correlation that is more accurate than the existing ones.

Garcia-Martin et al. [156] have developed and implanted, at the Plataforma Solar de Almeria (PSA), an automatic control system that allows appropriate distribution of temperature in a

volumetric receiver, based on a heuristic knowledge-based heliostat control strategy. They have also reported the tests details and the results.

4.1.4. Enhancement

Lenert and Wang [157] have presented a combined modeling and experimental study to optimize the performance of a cylindrical nano-fluid volumetric receiver. Their results suggest that optimized nano-fluids have significant potential as receivers for CSP systems because their efficiencies are expected to exceed 35% when coupled to a power conversion cycle.

Cheng et al. [158] have developed a general numerical modelling method and homemade unified code with the MCRT to simulate the thermal conversion process of REFOS-SOLGATE pressurized volumetric receiver. They have pointed out to the fact that the non-uniformity of the radiation flux density distribution is very significant; it could reach the maximum at the center-left area near the symmetry axis, and the minimum near the pressure vessel wall, with the order of magnitude of 8 and 3, respectively. The proposed design-simulation tool is very powerful for simulating other CSP systems and it is capable of providing behaviour information on many parameters and phenomena difficult to study experimentally.

Cheng et al. [159] have combined the Finite Volume Method (FVM) and the Monte Carlo Ray Tracing (MCRT) method to examine the effects of geometric parameters of the compound parabolic concentrator (CPC) and the properties of the porous absorber on the performance of solar conversion process in pressurized volumetric receiver (PVR). He has concluded that CPC exit aperture has much larger effects on the characteristics and the performance of the PVR than that of the CPC entry aperture with a constant acceptance angle.

Veeraragavan [160] has developed an analytic model through the combination of radiative and convective losses coefficients to evaluate the effect of design features and solar radiation on the performance of volumetric receiver with nano-particle-HTF. He has selected the heat transfer fluid VP-1 suspended graphite nano-particle as a case study. The obtained results have been very interested. He has then pointed out that the proposed model is a good tool to optimise the efficiency of various receiver configurations.

Arai et al. [161] have considered transient radiative heating of a semi-transparent liquid suspension in taller solar receivers. They have found that volumetric receiver with such fluid media would have higher performance.

Buck et al. [162] have developed a hybrid receiver made up of a tube absorber and an open volumetric receiver. They have compared its performance with that of PS10 saturated steam receiver. The Authors have indicated that the new concept offers many advantages; in particular, the reduction of thermo-mechanical stress induced by variations in the extent of the evaporation section during transients as occurred it has occurred in Solar One plant. They have indicated that the proposed receiver could improve the net annual energy by 27% compared with the solar air heating system.

Garcia-Casals et al. [164] have studied the possibility of enhancing duct volumetric receiver performance by analyzing the effect of numerous design parameters, in particular selectivity mechanisms. Unlike A. Kribus et al. [140] and Pitz-Paal et al. [163], they have shown that modular absorber design with small sizes is not necessary because the duct receiver appears to be inherently stable.

Pritzkow [165] has simulated the dynamic behavior of volumetric receiver during cloudy periods. He has then proposed an attenuator to protect the receiver from transient conditions and clouds.

4.2. Solar cavity receiver

4.2.1. Basic concept

In a cavity receiver, the radiation reflected from the heliostats passes through an aperture into a box-like structure before impinging on the heat transfer surface.

4.2.2. Design

James and Terry [166] have investigated the thermal performance of five cavity receivers of different geometries comprising spherical, hetero-conical, conical, cylindrical and elliptical. They have found that the rim angle and cavity geometry have a strong effects on the energy absorption efficiency.

Zhilin et al. [167] have provided a quick overview of the basic design of cavity air receiver. They have also reported the design data of the first demonstrative hybrid solar gas turbine of 70 kW in Nanjing, China.

Yu et al. [168] have evaluated and simulated the dynamics performance of solar cavity receiver for full range operation conditions using combined model which mainly couples the radiation–heat conversion process and three heat transfer parameters. They have also tested the effect of wind and DNI on the performance of DAHAN receiver. Their results show that wind angle or velocity can obviously influence the thermal losses.

Fang et al. [169] have described a methodology for evaluating thermal performance of saturated steam solar cavity receiver under windy environment. To this end, the Monte–Carlo method, the correlations of the flow boiling heat transfer and the calculation of air flow field were coupled to assess absorbed solar energy. They have concluded that the air velocity attained the maximum value when the wind came from the side of the receiver and the thermal loss of receiver also reached the highest value due to the side-on wind.

Yang et al. [170] have used Computational Fluid Dynamics (CFD) to look into the distributions of temperature, heat flux and the heat transfer characteristics of a molten salt tube receiver of a central receiver system. They have concluded that temperature distribution of the tube wall and HTF is irregular and the heat flux of the exposed surface rise with the rise of molten salt velocity.

Sobin et al. [171] have considered the design of the receiver thermal cyclic life. They have found that asymmetrical shapes of the receiver caused by expected flux by suitable sensing and controlling the energy intensity.

Li et al. [172] have performed a steady-state thermal model for 100 kW t molten salt cavity receiver. They have analyzed the effect of optical parameters on the design of such a receiver.

Hinojosa et al. [173] have presented the numerical results of natural convection and surface thermal radiation for open cavity based on Boussinesq approximation.

Gonzalez et al. [175] have numerically analyzed the heat transfer by natural convection and surface thermal radiation in a two-dimensional square cavity receiver with large temperature gradients. Comparing their results to those of Hinojosa et al. [173] and Chakroun et al. [174], they have concluded for larger Temperature gradients, i.e., between 200 K and 400 K, the radiative heat transfer is more important that convective heat transfer.

Yang and Yang [176] have considered the relation between the heat transfer performance and the efficiency of a molten salt tube receiver. They have found that the Nusselt number of the spiral tube is on average about three times larger than that of the smooth tube.

Paitoonsurikarn and Lovegrove [177] have numerically examined three different cavity geometries. They have then established a correlation of the Nusselt number for natural convection.

Dehghan and Behnia [178] have developed a model mixing the three heat transfer modes in an open-top vertical cavity receiver. They have obtained that natural convection is the major mode of heat transfer.

Boehm and Nakhaie [179] have developed a flux-on method for predicting the heat losses of molten salt receiver. They have the new method with other numerical methods, as well as, with experimental data of National Laboratories' molten salt electric experiment (MSEE) with good agreement.

Carasso and Becker [180] have proposed a flux-off method to estimate the heat loss of receiver. They have obtained that this latter is equal to the change in enthalpy of the working fluid when outlet fluid temperature is in a steady state condition.

Kumar and Reddy [181] have developed a 2-D model to predict the natural convection heat loss of cavity receiver. They have found that convection heat loss is the maximum at 0° and declines monotonically with a rise in angle up to 90°.

Clausing [182] has presented an analytical model for convective heat loss of a large cavity receiver based on the energy balance between the hot receiver and the energy transfer across the aperture. He has divided the internal area of cavity receivers into a convective zone and a stagnant zone, to compute the convection heat losses, examined the effect of the geometric design of the aperture on the heat transfer coefficient.

Clausing [183] has compared the results between analytical predictions [182] and experimental results of cubical cavity receiver with good agreement.

Taumoefolau et al. [184] have carried out a theatrical study of natural convective loss of an electrically heated cavity receiver with different inclination angles varying from -90° to $+90^{\circ}$ and temperature ranging from 450 °C to 650 °C and ratios of aperture to cavity diameter between 0.5 and 1. Their results were in good agreements with the experimental results.

Li [185] has developed a steady model that easily estimates the heat losses from cavity receivers.

Ferriere and Bonduelle [186] have proposed a lumped parameter model for the solar receiver of France Thémis plant. They have simulated the time-dependent parameters involved in the energy balances.

Fang [187] has proposed an iterative method, based on Monte–Carlo Ray Tracing technique, to determine surface temperature and to investigate the performance of cavity receiver under windy conditions.

4.2.3. *Experiment*

Kribus. et al. [188] have experimentally developed and tested a multistage solar cavity receiver to reduce the heat losses by dividing the aperture into separate stages according to the irradiance distribution levels. They have been able to get an air exit temperatures of up to 1000 °C.

Melchior et al. [189] have designed, fabricated, and tested a 5 kW cylindrical cavity receiver comprising a tubular absorber, for performing thermo-chemical reaction. The reactor has been modeled using a 2D steady-state model coupling the three heat transfer modes to the chemical kinetics, and solved using Monte Carlo and finite difference techniques. The prototype has achieved solar-to-chemical energy conversion efficiency of 28.5% at a reactor temperature of 2300 K for an input solar power per unit length of absorber of 40 kW/m.

Hahm et al. [190] have fabricated and tested a cone concentrator combined with a solar cavity receiver at the solar furnace in Cologne for comparison to that of single cavity. They have found that the optimum cone geometry strongly depending on the cavity model.

Yeh et al. [191] have reported an experimental technique of modeling with water as a HTF having different densities. They have found that the flows inside the cavity receiver were laminar when Grashof number in the order of 107, other than, a transition to turbulent when the Grashof number exceeded 107.

Chakroun et al. [174] have reported the experimental Nusselt numbers for a tilted open cavity receiver with polish aluminum walls.

Zhang et al. have performed experiments to investigate the transient thermal performance (incident power and flow rate) of a 100 kWt molten salt cavity receiver that use electric source as incident radiation. They have obtained that the instantaneous efficiency of the receiver in pro-steady state is affected by input power but is not by changes in the flow rate; however, the closer the input power is to the design value, the less the efficiency variation. [192]

Taumoefolau et al. [193] performed experiments, using electric heat source, to investigate the performance of cavity receivers. They have then established a relationship between the natural convection heat loss and the inclination of the receiver.

Quere et al. [194] have performed experiments to look into laminar natural convection in an open cubical cavity with isothermal sides. They found that the convection heat loss is strongly dependent on the cavity inclination.

Reynolds et al. [195] have numerically and experimentally estimated the heat loss from trapezoidal cavity with hot plate for flow visualization. He has found that the heat loss estimated by FLUENT was under-predicted, i.e., about 40% less than the experimental results.

Prakash et al. [196] have experimentally and numerically investigated the steady-state convection heat loss from a cylindrical cavity receiver with greater aperture diameter to the cavity diameter ratio. They have then proposed Nusselt number correlations based on the receiver aperture diameter.

Baker and Faas's [197] have described the CESA-1 cavity receiver including receiver controls, cold and warm receiver start-ups and the receiver transient response to cloud passage during operation.

Zhang et al. [198] have applied the transfer function method (TFM) to estimate the outlet temperature of molten salt cavity receiver and several experiments were conducted to verify the method. The authors obtained a relative error of 14.69% when sharp variation in the input power accrued. Consequently, they suggested some enhancements in the model for reducing the influence of flow rate variation on the thermal performance test results.

Wu et al. [199] have performed experiments to examine the heat transfer characteristics of molten salt in a circular tube. They found a good agreement between the experimental data of molten salt and numerical correlations.

4.2.4. *Enhancement*

Montes et al. [55] have put forward a new design for the active absorber surface of cavity receivers. In this new design the fluid flow pattern has been divided according to the radiation flux map symmetry. It can then provide uniform temperatures of HTF at the receiver outlet. Irreversibility can also be decreased by circulating the fluid from the lower temperature region to the higher temperature region of the absorber surface.

Hischier et al. [200] have proposed a new receiver design, for combined cycle power plants, consisting of two concentric cylinders. To analyze the temperature distribution and thermal efficiency as a function of the geometrical and operational parameters, they have developed a 2D-steady state model combining the three heat transfer modes. They have been able to

attain an outlet air temperature of 1000 °C at 10 bars; and consequently a thermal efficiency of 78%.

Teichel et al. [203] have developed a semi-gray radiation model based on a method originally proposed by Beckman [201] and Gebhart [202], and using extended view factor called "F-hat". This method has been used to investigate the effect of surface emissivity on the performance of solar cavity receiver. The results have revealed that optimal distribution of emissivities into a two-band selective surface can improve the receiver efficiency by 0.7% compared with that of 0.95 emissivity for all wavelengths.

In order to improve the receiver design and efficiency, Boerema et al. [56] have compared the thermophysical properties of liquid Sodium to that of Hitec heat transfer fluid using a simple tubular receiver model. Hitec is a 53% KNO_3+40% $NaNO_2$+7% $NaNO_3$ternary molten salt. The results indicates that the use of Sodium offer the possibility of reducing the absorption area by 57% and rising the absolute efficiency by 1.1%; this is in addition to its wide range operation temperature (from melting point 97.7 °C to boiling point 873 °C).

Behnia et al. [204] have investigated the radiation and natural convection in a rectangular cavity filled with a non-participating fluid. They have concluded that external convection weakens the internal circulation, while radiation strengthens the flow.

Wu et al. [205] have conducted a 3-D numerical study to examine the effect of geometric design of heat pipe receiver on natural convection characteristics. They have then proposed a new accurate correlation of Nusselt number that can estimate natural convection heat losses.

Leibfried and Ortjohann [206] have focused on the heat losses of cavity receivers at various inclination angles. They have proposed new correlations based on correlations suggested by Clausing and Stine.

Fang et al. [207] have developed a computational model to simulate the start-up performance of a saturated steam solar cavity receiver. The selected receiver in their study consists of six-side prism of absorber tubes with inclined top and bottom faces. They have examined three starting strategies including cold start-up, warm start-up and hot start-up and have founded that the convective heat loss very significant in this phase; even at the end of start-up, the convection heat loss is1.5 times more than the radiative heat loss.

Balaji and Venkateshan [208] have considered natural convection in combination with surface radiation in a rectangular enclosure of a different aspect ratio filled with a non-participating medium. They have found that, for aspect ratios greater than or equal to 2, the convection and radiation mode of heat transfer could be decoupled. They have then proposed separate correlations for the convection and radiation Nusselt number were proposed.

Maffezzoni and Parigi [209] have investigated the dynamic and control of the solar receiver under flux variations. They have proposed the control of steam pressure to avoid material thermal stresses that may lead to receiver failure.

Ben-Zvi et al. [210] have proposed and analyzed a hybrid concept for solar receiver that consists of two parts, i.e., external for boiling the steam and a cavity for its superheating; the tow sections can be work separately and facing different parts in a surrounding heliostat field (170 MWth) of larger solar tower power plant producing superheated steam at 550 °C and pressure of 150 bars, and therefore, have achieved thermal efficiency of 85% at the design point.

4.3. Solar particle receiver

4.3.1. Basic concept

Particles receivers is perhaps less known than others solar receiver applied in power towers, but not less interesting. The particle receiver, as its name indicated, uses solid particles to absorb concentrated direct solar irradiation that serve as HTF and storage medium. This type of solar receiver can achieve high temperature since solar flux is directly absorbed by the heat transfer fluid and heat exchangers are then not needed [61].

4.3.2. Design

Tan and Chen [54] have reviewed the solid particle receivers used in water-splitting thermo-chemical process for hydrogen production. They have consequentially described the conceptual design, mathematical formulation, experimental and numerical studies. They have also analyzed the effect of common factors that affect the receiver performance.

Grena [213] has simulated the temperature distribution in 3 m fall solar particle receiver. He found that his results are in to good agreement with that of Chen et al. [211] and Evans et al. [212]. The results have shown that the local temperature can have a non-uniform distribution depending on the size of the particles and the exposition time.

Meier [215] has used CFD to simulate combined convective and radiative heat transfer in falling particle receiver of 1.5 MW hybrid (solar-fossil) cement plant, He has compared his results with that of Hruby [214]. He has found that particles with a diameter smaller than 300 lm can be affected by convective air streams, thus he proposed air and transparent windows to reduce convective losses

4.3.3. Experiment

Kim et al. [216] have carried out experiments on small scale solid particle curtain receiver to determine the variation of velocity, solids volume fraction, curtain thickness, and curtain opacity over a drop height of 3 m. They have also simulated the characteristics of the solid particle by MFIX code. Their simulation results were in good agreement with the experimental results in terms of falling particle velocity and solid fraction.

Kim et al. [217] have experimentally and numerically analyzed the wind effect on particle loss in small solar particle receiver. For that, they have considered three factors, namely, the wind velocity, the angle of the attack, and the depth of the cavity. They have found that a 45 deg angle of attack, less than 0.46 m of the cavity depth, and a 6.5 m/s wind velocity can induce 10% particle loss, whereas the wind with 90 deg angle of attack do not affect significantly particle curtain.

Bertocchi et al. [218] have experimentally investigated the outlet temperature of a solar particle receiver of 80 mm diameter aperture. They have been able to attain 2100 K using nitrogen, 1900 K using CO_2, and 2000 K using air as fluids media. They have then achieved an 80% thermal efficiency at the highest mass flow rates without any major failures.

4.3.4. Enhancement

To determine the radiation characteristics of suspended carbon particles solar receiver, Klein et al. [219] have developed a model that uses improved Mie theory, taking into account molecule collisions in the energy transfer region. They have found good agreement between the simulated results and the experimental data. They have come to the conclusion that particles whose effective radius is between 100 nm and 1000 nm are optimum in absorbing solar radiation.

Tan et al. [220] have numerically investigated the performance of solid particle solar receivers with and without the protection of aerowindow, under different wind conditions. They have concluded that the aerowindow significantly reduces energy losses.

Jafarian et al. [223] have introduced a novel hybrid chemical looping combustion (CLC) process, that use the oxygen carrier

particles in a CLC system to provide diurnal thermal energy storage for cavity receiver CRS. The performance of the SCR–CLC hybrid system have been performed using ASPEN PLUS software with the compositions of products being taken into account by the Gibbs minimization method with the assumption of ideal gas behavior. Their results have been validated by data of Hong et al. [221,222] with a relative error of 6%.

5. Power conversion system

In the power conversion system thermal energy produced at the receiver is converted into electricity with an efficiency that depends on the thermodynamic cycle and components performance. The three mostly used thermodynamic cycles are: the Brayton cycle (SCR-BC), the Rankine cycle (SCR-RC) and the combined cycle (SCR-CC). However, it must be noted that hybrid operations are used to improve performance. In this part, a review of the studies carried out on SCR-BC, SCR-RC and SCR-CC, as well as, control strategy is presented.

5.1. Solar central receiver—Brayton cycle (SCR-BC) system

5.1.1. Basic concept

The basic concept of SCR-Brayton cycle consists of a heliostats field, a high tower with volumetric air receiver atop and an adapted gas turbine that is usually installed close to the receiver to reduce additional energy losses at interconnections (at the compressor outlet and combustor inlet). The concentrated solar radiation in the receiver will heat the air, which flows at high pressure coming from the compressor of a gas turbine, up to 100 °C. This air feeds the combustion chamber of the gas turbine, which increases the temperature to more than 1000 °C. The main advantages of this technology are a greater efficiency due to the high operating temperature and an efficient hybridization.

5.1.2. Design

Using both TRANSYS-STEC and Thermoflex softwares, Barigozzi et al. [224] have simulated the real off-design performance of a commercial solar hybrid gas turbine. They have come to the conclusion that the hybridization increases pressure losses and reduces compression ratio, and thus, lowering then the overall performance.

Considering the actual location of the first solar thermal power plant (SPP1), Behar et al. [225] have developed a mathematical model to evaluate the behavior of large scale solar hybrid gas turbine of 50 MW, under Algerian desert climate conditions. The simulation of annual performance has shown that the overall efficiency and the solar electricity ratio could reach 32% and 85%, respectively. Moreover, such a hybrid concept is able to save about 2000 t/year of fossil fuel.

Sinai et al. [226] focused their work on the hybrid mode of CRS-GT and concluded that hybrid gas turbine has numerous merits including potential for reducing costs, higher efficiency, and high land utilisation efficiency, sensitivity to load fluctuations, friendly environmental, easy start, and more effective equipment utilization than any other CSP technology.

5.1.3. Experiment

Heller et al. [227] have reported on the system configuration, the components efficiency and the operation experiences of SOLGATE project. In this project, the aim was to develop a solar receiver cluster for hybrid solar gas turbine and to demonstrate the operational ability of such a system. They have found that the cluster solar receiver can heat up pressurized air up to 1000 °C without major problems.

Buck et al. [228] have tested and modified a hybrid GT with a pressurized volumetric air receive. They have examined the concept at several configurations and the potential of such technology to become competitive with conventional plants.

Fisher et al. [229] have experimentally examined the performance of CRS- hybrid GT in both hybrid and fossil fuel only modes. They concluded that solar hybrid gas turbine operation is technically ready for commercial applications.

Dickey [230] has performed experiments and simulations of a micro solar only CRS-GT. He has been able to therefore confirm that such a concept has a potential to produce power from solar energy without back-up.

Korzynietz et al. [89] have reported the design concept of Solugas research project. They have also presented simulation studies of the three main subsystems of the demonstration plant.

5.1.4. Enhancement

Livshits and Kribus [231] have analyzed the thermodynamic performance of steam-injection hybrid solar gas turbine. The low cost solar collectors have been proposed to generate steam. They have used a simplified model implanted in Honeywell Unisim process software to simulate the performance of the hybrid cycle. The results were higher overall conversion efficiency of 40–55% due to the injected water that provides an incremental efficiency of 22–37% and solar electric efficiency of 15–24%.

Bhon et al. [232] have introduced the technique of solar preheating-Brayton cycle and evaluated its effects on the system performance. They have found that the proposed design provides higher efficiency. The solar fraction is has nevertheless to be limited if higher performance to be attained.

Pak et al. [233] have suggested a hybrid solar fossil system that employs a CO_2 as working fluid. This CO_2 has been recovered using the method of oxygen combustion. They have found that solar conversion efficiency becomes significantly higher than that of conventional hybrid solar gas turbines that utilize air as working fluid.

Pak et al. [234] have introduced a solar hybrid GT that recovers the CO_2 resulting from burning fossil fuel in the combustor. They have then recommended CO_2-capturing power process to energy saving and for reducing carbon dioxide emissions.

Schmitz et al. [235] have suggested the use of pressurized air solar receiver with secondary concentrator and an elliptic heliostat field design for hybrid solar gas turbine systems of 50–200 MW. They reached the conclusion that the single design is suitable for small power plants while the multiple elliptic fields are better suited for larger power plant.

Garcia et al. [236] have developed an advanced model for performance prediction of hybrid solar GT. The model takes into consideration climatic conditions and technical data of the major components including solar field, solar receiver and turbine.

Behar et al. [237] have numerically simulated the performance of commercial solar hybrid gas turbine. Their results have been very interested. They have then proposed the modification of gas turbine in Algerian desert into hybrid solar-natural gas power plant.

5.2. Solar central receiver—Rankine cycle (SCR-RC) system

5.2.1. Basic concept

5.2.2. Design

Zoschak and Wu [238] have examined seven configurations that integrate concentrated solar radiation by CRS into solar hybrid steam cycle of 80 MW, including feed-water heating,

water evaporation, steam superheating, combined evaporation and superheating, steam reheating, air preheating, and combined air preheating and feed-water heating, and the energy balance for each hybrid cycle. Applying the energy balance, they have found that the scheme that uses solar heat for both evaporation and superheating is the most suitable for converting solar energy into electricity.

Chen et al. [239] have reported the design and the engineering of 1.5 MWsolar tower plant in China. They have anticipated that such a solar system is able to save about 3.92E+08 GJ and reduce greenhouse gas emissions by 4.17E+04 t of CO_2 compared to conventional power plants.

Yang et al. [240] have estimated the energy cost, the electricity production, and the GHG emissions of 1.5 MW solar tower power during a period of 20 years. They have found that an energy cost intensity of 1.21 MJ/MJ and have indicated that such a plant is able to reduce 0.31E+06 t of CO_2 compared to conventional coal-fired power plants.

Yu et al. [241] have combined the collector and receiver models using STAR-90 software to simulate the steady and dynamic performance of DAHAN solar tower power. Their results have suggested some improvements in receiver components design.

Xu [242] has applied a modular modeling method to develop the dynamic simulation models of Dahan plant, based on STAR-90 simulation software.

Yao et al. [243] have described the basic flow calculation of the key components in CRS and their integration to be a whole plant model. In this work the heliostat field has been designed using HFLD code and the total power plant simulated using TRNSYS software.

Yao et al. have presented a simulation model to be use for predicting the performance of the DAHAN solar plant that uses the Rankine cycle to convert solar energy into electricity. In this model the optical ray tracing method and CFD approaches have been combined to grant accurate results [244].

Wang and Yao [245] have reported the design and data of DAHAN power plant.

Yebra et al. [246] have developed a dynamic model for the simulation and the control of the CESA-I power plant taking into consideration typical operation cycle with a real perturbation introduced by start-up, shutdown and passing cloud.

Moon et al. [247] have developed a program using Visual Basic 6.0 to predict the performance of Dahan solar thermal power plant.

Alexopoulos and Hoffschmidt [248] have overviewed the solar tower technologies. They have indicated that such technology offers many benefits for both power generation and environment. They have then suggested the implantation of central receiver system in Greece and Cypru.

Gall et al. [249] have used a linear predictive controller to regulate the receiver outlet temperature in volumetric air tower power plant. They have found that the model is capable for predicting future behaviour of the plant with regard to changes in actuating variables.

Honeywell [250] has developed a mathematical model to simulate the dynamic performance of solar tower pilot plant during clouds passage.

5.2.3. *Experiment*

Hennecke et al. [251] have reported the technical data about the engineering and the development of the Solar Power Tower Jülich. The Jülich central receiver is used atmospheric air as the heat transfer fluid to generate a steam that used to drive a Rankine cycle. The basic design of this power tower is represented in Fig. 18.

Lowrie [252] has conducted experiments on a pilot central receiver system. They have focused on the effect of cloud passage on the performance of central receiver system, in particular its key subsystem, the receiver.

McDonnell [253] has experimentally studied the performance of 10 MW central receiver.

5.2.4. *Enhancement*

McGovern and Smith [254] have investigated the effect of thermal conductance and receiver irradiance on the optimal receiver temperature and the solar conversion efficiency of five power cycles, i.e., Rankine cycle, solar parabolic-trough, solar central-receiver, direct-steam and molten-salts power plant. they have concluded that, for maximum efficiency and optimum receiver temperatures, sub-critical Rankine cycles is preferred for parabolic trough power plants, while super-critical Rankine cycles is suitable for central receiver systems.

Coelho et al. [255] have analyzed numerous possibilities of hybridising biomass and volumetric receiver CRS power plants. They have used Ebsilon Professional software to design and optimise the power conversion system, while the solar subsystems, i.e., heliostat field and volumetric receive have been designed and optimised in HFLCAL software. The control strategy and power plant economics have been analyzed using a mathematical program implanted in Excel. The authors have selected the Portuguese Algarve region for their study. They have found that the larger the hybrid plant, the better are the performance; for instance, 10 MWe power plant can have LEC of 0.108 €/kW h with twice the annual efficiency and lower costs than solar only tower system of 4 MWe. The proposed concept could reduce biomass consumption by 17% compared with conventional power plant of similar capacity.

Xu et al. [256] have focused on the energy and exergy analysis of the solar tower power plant that uses molten salt as the heat transfer fluid. The aim has been to identify the source and regions of energy and exergy losses. They have found that the power

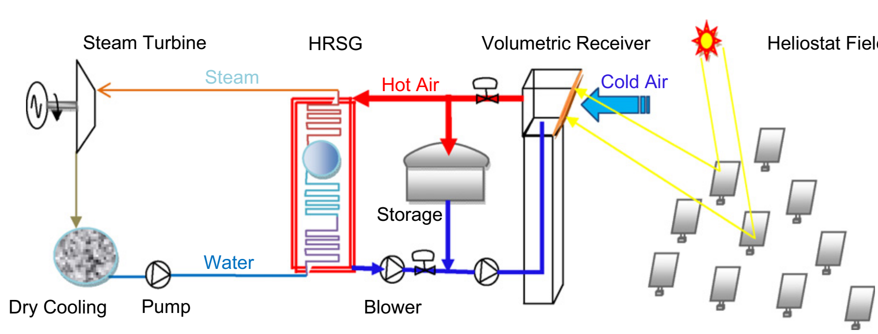

Fig. 18. Solar power tower with atmospheric air volumetric receiver (Jülich-Like plant).

conversion system accounts for more than half of energy losses (53.3%) while major part of the exergy losses take place in the receiver (44.2%), followed by the heliostats field (33.1%). The Authors have then proposed advanced power cycles to improve energy and exergy efficiencies such as reheat Rankine cycle (exergy efficiency rises from 24.5% to 25.6%) and supercritical Rankine cycle (exergy rise up to 27.4% compared with simple Rankine cycle).

Álvarez et al. [257] have proposed the use of Mixed Logical Dynamical (MLD) approach, instead of classical approach, transfer functions, to model the TSA hybrid system located in the CESA at PSA. They found that their results are in good agreement with experimental data.

Ahlbrink et al. [258] have coupled three simulation environments, i.e., STRAL, LabView and Dymola software, to investigate transient performance of solar tower power plants. The start-up, the failures and the case of cloud passage are investigated. They have then created a module of an open volumetric air receiver for transient performance and implanted it in the Modelica software library.

Griffith and Brandt [259] have developed a mathematical model to investigate the thermal performance and the costs of CRS- hybrid fossil power plant with storage. Their results have been shown the capability of the proposed model for estimating the hourly solar energy collected and the amount of fuel consumption. They have found that when the capital investment of the CRS-hybrid plant is 2.5 times lower than that of only fossil plant, the CRS-Hybrid fossil plants become competitive to conventional thermal power stations.

Hu et al. [260] have developed a powerful software called THERMOSOLV. This software has been used to evaluate the technical and economic feasibility of solar aided-steam cycle, for diverse configurations, for CSP families and different locations.

Tora et al. [261] have introduced a new methodology to find out the optimal mix between solar and fossil energy that allow stable power output from hybrid power plants.

Xu et al. [262] have developed a dynamic simulation model for thermal energy storage of larger central receiver system. They have simulated the recharge and discharge processes based on the heat exchanger model and steam accumulator model. The results have been indicated that during operation, the steam outlet temperature decreases sharply at the rapid opening of the regulating valve.

5.3. *Solar central receiver—Combined cycle (SCR-CC) system*

5.3.1. *Basic concept*

5.3.2. *Design*

Schwarzbozl et al. [263] have carried out a theoretical investigation on the performance of three prototypes of hybrid solar gas turbine under two different climates: Intercooled recuperated two shafts, reheat recuperated single shaft and combined cycle power plants of 1.4 MW, 4.3 MW and 16.1 MW, respectively. In this work, the HFLCAL software has been applied to evaluate solar system, and the TRANSYS-STEC used to predict the thermal performance of the power block. The field efficiency matrix tool is used to link the software and the simulation results showed that solar to electric efficiency of 14–19% is feasible.

Kribus et al. [264] have studied the feasibility of solar hybrid combined cycle with beam down optical central receiver. They have developed a software tool to evaluate its performance. Their results have indicated that solar gas turbine combined cycle offers a lot of advantages compared to other solar power concepts. Moreover, it can be competitive with fossil power plants.

Kolb [265] has economically compared various configurations of hybrid and solar only CRS- power plants. He has found that CRS-CC and CRS-Coal- fired plants are more competitive than solar only systems.

Horn et al. [266] have technically and economically compared two technologies of CSP for integration into CC: HTF-trough and volumetric air receiver. Their findings have been that the hybrid CC with air tower is as efficient as hybrid plant with trough technology. They have also indicated that such a concept presents an attractive option for renewable electricity in Egypt.

Garcia et al. [267] have compared six simulation environments for solar tower power investigation: UHC, DELSOL, HFLCAL, MIRVAL, FIAT LUX and SOLTRACE. They have then classified them into two groups. The first one comprises optimization codes HFLCAL, UHC-RCELL, and DELSOL. The second group includes performance analysis codes such as FIAT LUX, MIRVAL, UHC-NS, and SOLTRACE.

Lippke et al. [268] have presented the thermodynamic designs SCR-RC and SCR-CC; both used a PHOEBUS air volumetric receiver. They have compared the tow power cycle and found that SCR-CC offers better performance than of SCR-RC system, if it is well designed.

5.3.3. *Experiment*

No experiments until now.

5.3.4. *Enhancement*

Bonadies et al. [269] have proposed the use of thermal storage to enhance the availability of CRS-CC. The operation duration for this new hybrid cycle can therefore be extended to 17 h using storage and with less running time for the GT compared with CRS-CC without storage.

Heide et al. [270] have introduced new concept of CRS-CC that integrate concentrated solar radiation directly into the GT, between the compressor outlet and the combustor inlet. Such a configuration is illustrated in Figs. 19 and 20. The results have indicated that higher share of solar energy is possible in this concept.

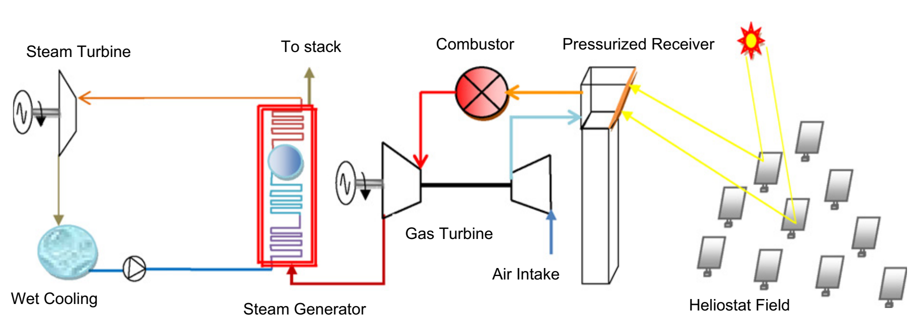

Fig. 19. Solar hybrid gas turbine combined cycle.

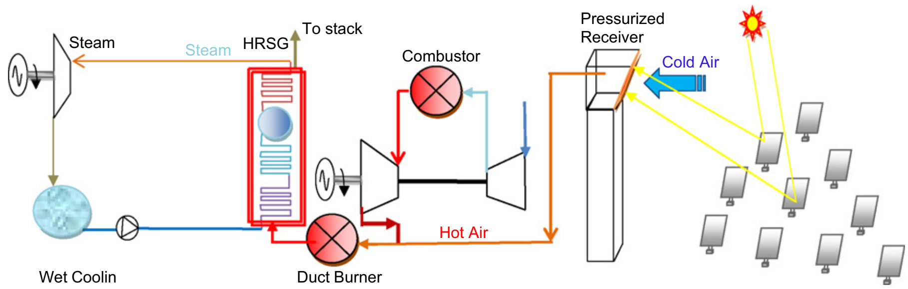

Fig. 20. Combined cycle with solar air tower and gas turbine.

Rheinlander et al. [271] have carried out the performance and cost calculation for SCR-RC and SCR-CC that used for both power generation and water desalination. They have compared their performance to those of conventional fossil plants. Their results indicated that that the costs of fresh-water are close to or even lower than those of conventional cogeneration plants.

Ramos and Ramos [272] have introduced a new parametric optimisation procedure for optimizing a central receiver system. The procedure has been based on eleven design variables, seven design parameters and insolation data. They have checked their proposed method on two typical plant, i.e., one with 900 heliostats and the other equipped with 3000 heliostats, using three state of the art algorithms, i.e., NSPOC, MINUIT and Genetic algorithms. The results has been shown that the three algorithms provide the same basic plant design with different values of some of additional parameter, Nevertheless, essential parameters for the plant design are approximately the same.

Spelling et al. [273] have focused on the thermodynamic and economic performance of solar only SCR-CC with volumetric receiver. They have used a population-based evolutionary algorithm for optimization, and obtained that the combined cycles ranging from 3–18 MWe can achieve efficiencies in the range of 18–24%, with Levelized electricity costs in the order of 12–24 UScts/kW he.

Price et al. [274] have proposed the use of Air-CRS to power a combined cycle. Their results have been indicated the solar energy can be converted into electricity, at higher exergy level into a Brayton cycle, especially, when high concentration ratio and high temperature are possible.

Jamel et al. [42] have presented a review of studies and published papers on hybrid solar thermal power plants, for the last three decades. They have classified the power conversion systems into three groups, i.e., hybrid-BC, Hybrid-RC and Hybrid-CC. The Authors reported the percentages of using different types of CSP technologies for hybridization into power conversion cycles.

6. Analysis and outlook

The present review indicated that research on the central receiver technology is growing rapidly. Four countries, namely, the USA, Spain, China and Germany, have launched enormous R&D projects. They are also installing many commercial power plants. This is particularly true for the case of the USA that is already operating and announcing many projects based on power tower concept.

The reviewed published papers and studies are focused on the three main subsystems of the central receiver solar thermal power plants, i.e., the heliostat field, the solar receiver and the power conversion system. For the heliostats field layout, the existing designs have been optimised and some advanced in layout such as spiral configuration are proposed to improve land utilization and efficiency. Furthermore, the Micro Tower Configuration introduced recently is very promising and it is still under development. In order to increase the accuracy of the control and tracking system, two sun-tracking methods are usually applied in CRS: the Azimuth–Elevation (AE) and Spinning–Elevation (SE). However, this latter allows more solar energy collection at the receiver and reduces spillage losses by 10–30% [28].

The number of published papers interested on the solar receivers is very important because it is the key elements of the power tower plant. About 26% of the total papers have focused on the cavity receiver followed by volumetric receiver 15%. For Particle receiver, there has been little interest; nevertheless, three momentous research projects very recently announced in USA with more than 11.6 $ million would bring such a concept to the forefront. A detailed analysis of published papers is presented in Fig. 21.

For a power conversion system many improvements have been suggested. However, the lack of commercial experience for some configurations, in particular combined cycle gear down this attractive concepts which prove their potential in fossil fuels power plants.

7. Conclusion

Concentrating solar power technology has been lately attracting a lot of attention. A sustainable effort is underway to develop its technology. Tough it has been reached the commercial maturity, there are still a lot of activities at different levels to improve its performance.

At the commercial levels the installed capacity has skyrocketed. Examination of the available data has shown that there has been an exponential increase in the installed power. At this level Spain and the USA followed by China are setting the place for a viable development of a CSP economy. At the regional level, Desertec initiative has been recently advocating and taking steps for the development of CSP in the Mediterranean region.

Though most of the installed CSP is of parabolic trough technology, the central receiver system (CRS) technology is gaining ground and is under consideration worldwide for many projects.

Besides the efforts is commercial development of CRS technology the action taken encompassed R&D activities for better understanding of the basic phenomena, design activities for the design of more efficient plants and prototyping and testing activities for improving the performance of the subsystems and of the systems.

The actions have not only been in improving the existing concepts but also in proposing innovative ideas.

The present study has reviewed in details the central receiver solar thermal power plants. This work shows that the World energy demand, energy costs and climate change are the main drivers of R&D activities. In other words, the market realities are

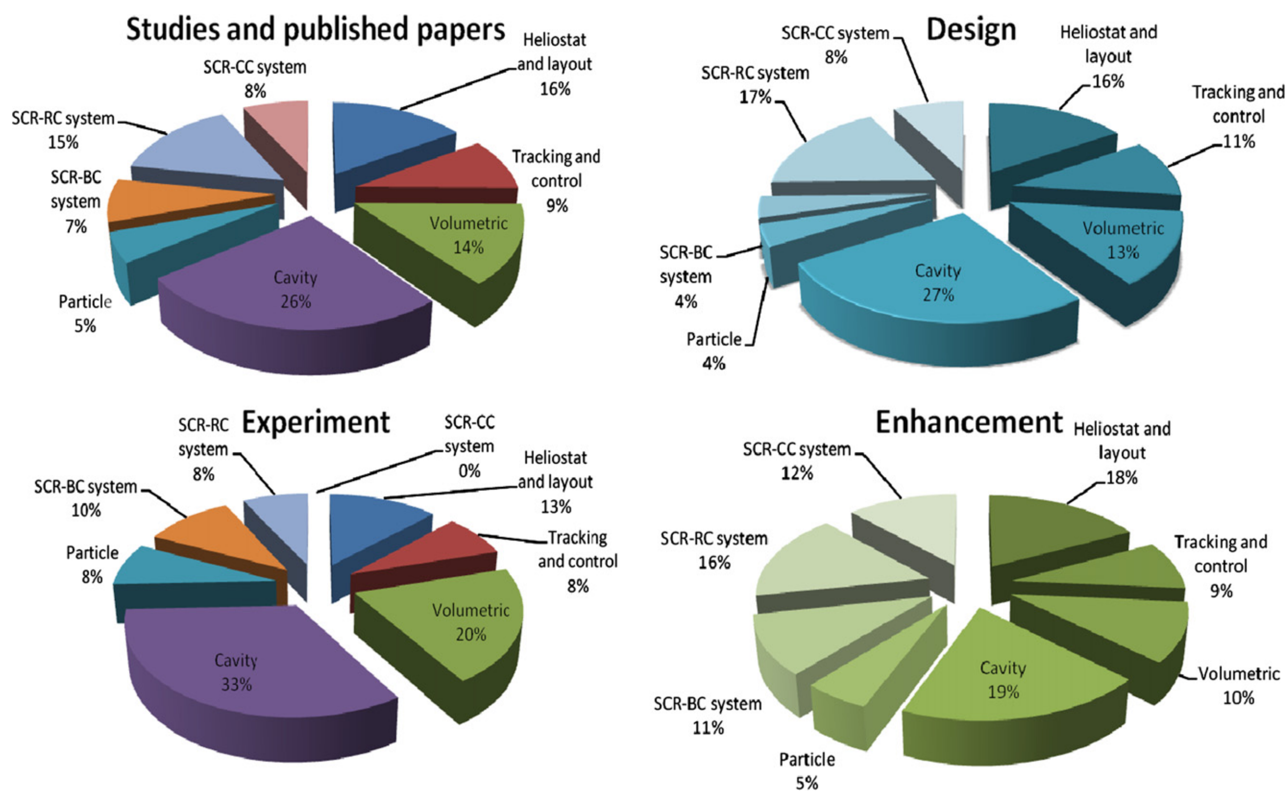

Fig. 21. Analysis of reviewed studies and published papers.

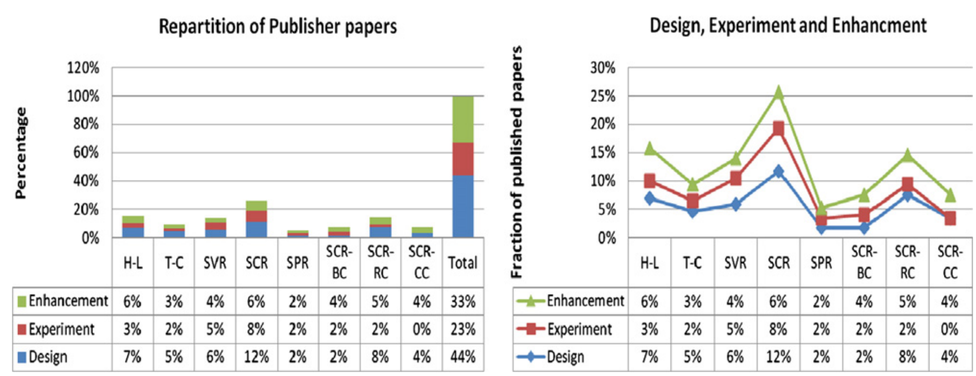

Fig. 22. Comparison of the fraction of published papers according to their subject, and purpose. R&D activities are strongly related to experiments (figure right).

strong drivers of R&D; and new technologies can progress rapidly from the laboratory, through pilot and demonstration scales, to commercial application.

For the heliostat field, most design studies were based on Monte-Carlo Ray Tracing Method and numerous codes, such as HFLD, have been developed to simulate the optical performance, and some Authors have suggested enhancements, such as farming under heliostats, to optimize land use and improve efficiency by using for example spiral layout.

About half of the reviewed studies have been focused on solar receiver. On this topic, about 26% of the review has dealt with cavity receivers, while 14% with volumetric receivers and only 5% with particle receivers. As indicated in Fig. 22, enhancements are strongly dependent on the number of experiments because tests have proven to be the best way for locating weakness and inefficient subsystems. It has been this way that many improvements have been possible. This is the case of Solar One that has been upgraded to Solar Two. That has been also the case of the additional steam Drum at the PS10 that has reduced thermal stress in the receiver and advanced their performance.

In this work, we have found that there has been a little interest in the particle receivers. This might be due to a lack of experience. This could also be due to the difficulties of integrating it into power conversion systems as the employed HTF is mostly particles (power cycles usually used water/steam or air).

For a power conversion cycles, about 30% of this review has dealt with this subject. A lot of configurations, hybrid systems and advanced concepts, have been investigated and analyzed in-depth using simulation tools and experimental data to validate the results. The SCR-RC with cavity receiver, such as in the case of PS10 and PS20, has been well designed and tested and recent studies have confirmed that supercritical and ultra-supercritical cycles are very promising for the improvement of efficiency. The SCR-BC has also been designed, tested and enhanced together with volumetric receiver, such as Solgate and Consolar. This configuration appears to be more promising as there is an increase interest in it in the

recent years. Simulation studies have shown higher performance for larger Brayton cycle and this is in support of the implantation of the first commercial hybrid gas turbine. According to the existing literature, the combination of Brayton and Rankine cycles is also very promising. There seems to be as much interest in this concept as there is in SCR-BC (8% for SCR-CC vs. 7% for SCR-BC); nevertheless no demonstration plant has so far been implanted.

One option for further research is the supercritical steam, or carbon dioxide, cycles such as those used in modern coal–fired power plants. With supercritical and ultra-supercritical designs, these power plants can reach thermal-to-electric efficiency levels of 42% to 46%. The application of this technology to solar towers, requires however more in-depth R&D activities. For the solar subsystems, the Micro Tower Configuration (MTC) appears to be one of the most promising options to reduce investments costs induced by higher tower and enhance optical efficiency as it is recently confirmed by simulation tools. Indeed, the larger the power plant, the higher is the tower and the highest are the investments costs. Such a concept appears to be quite attractive particularly in association with Brayton cycle.

To meets these targets, increase in research funding and a stronger integration of fundamental and applied research, together with demonstration programmes and market incentives are required to speed up the innovation stage. Fundamental research on solar radiation assessment, solar subsystems, heat transfer fluids and storage technology are needed for taking some advanced CRS concepts from laboratory-scale prototype systems out to commercial scale applications.

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